

Task 55 Towards the Integration of Large SHC Systems into DHC Networks

B-D1.2 Review of In Situ Test Methods for Solar Collectors and Solar Collector Arrays

IEA SHC FACT SHEET 55 B-D1.2

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| Subject: | Review of In Situ Test Methods for Solar Collectors and Solar Collector Arrays |
| Description: | This fact sheet presents three in situ test methods for solar collectors and solar collector arrays, namely <i>In situ Collector Certification (ICC)</i> , <i>Performance Check for Collector Arrays (PC)</i> and <i>Dynamic Collector Array Test (D-CAT)</i> . A comparison is made regarding their scopes and use cases, methodologies and outcomes, which could serve as a decision-making aid for stakeholders in selecting the procedure that best suits their needs. The analysis shows that the methods do not contradict, but rather complement each other. |
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| Download possible at: | http://task55.iea-shc.org/fact-sheets |

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Introduction

Large-scale solar thermal plants (>500 m² collector area, >350 kW_{th} nominal thermal power) are a cost-effective way to provide renewable heat. The market has experienced considerable growth recently, reaching a total installed and operated capacity of 1.62 GW (2.3 million m² collector area) worldwide by the end of 2019 [1]. The driving force has been solar district heating applications in Denmark, where the world's largest plant in Silkeborg (156,694 m² flat plate collectors; 110 MW_{th} capacity) started operating in December 2016 [2].

Building large-scale solar thermal plants requires a high initial capital investment, which is paid back over the lifetime of the plant (typically 20 to 25 years) with the revenue of the produced solar heat. To incentivize investments in new projects, it is essential to ensure a consistently high solar energy yields over the lifetime of the plant [3]. This has drawn attention to the necessity of reliable and meaningful test procedures. At the planning stage, the efficiency parameters of the deployed collectors are required as a basis for energy yield simulations. Test procedures also serve as a means of quality assurance at the start of the operation phase (commissioning) and on-going surveillance of the collector array performance.

At present, there are various activities for the development of such test procedures, which pursue different approaches and objectives. Three in situ test procedures are selected here for discussion:

- **In situ Collector Certification (ICC):** An annex has been added to the Solar Keymark Scheme Rules to enable the measurement of collectors for product certification in the field based on results from the German funded project ZeKon in-situ.
- **Dynamic Collector Array Test (D-CAT):** The Austrian funded research project MeQuSo developed methods for quality assessment of large-scale solar thermal plants under real operating conditions, based on similar physical foundations as the quasi-dynamic test method of ISO 9806 [4].
- **Performance Check for Collector Arrays (PC):** In ISO/TC 180 there is a new work item with a proposal for a simple method for checking collector field performance [5].

Thus, there are different possible approaches in place potentially creating confusion as to which is the most preferable method for a specific application. This fact sheet intends to provide clarity and transparency to manufacturers, plant designers and operators to be able to choose the suitable method providing them the information needed within the acceptable cost and time frame.

Additional information on the ICC [6] and D-CAT [7] methods are available in the final project reports. Within IEA SHC Task 55, two fact sheets covering the PC method have been produced: “*B-D2 Collector fields – Check of performance*” and “*B-D1.1 Application of PC Method to Large Collector Arrays*”. The basis of this fact sheet is a paper published by [8].

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Description of methodologies

In situ Collector Certification (ICC)

Introduction

Within the scope of the project ZeKon in-situ funded by the German Ministry of Economic Affairs and Energy, research was carried out into how a single collector in a field installation can be characterized for certification purposes on the basis of an adapted quasi-dynamic test method (QDT) known from ISO 9806. The necessary adaptations of the test method and a new Appendix P5.5 to the Solar Keymark Scheme Rules were developed, which describes the procedure and peculiarities of field measurements on the level of product certification. The flowchart in Figure 1 shows the process of the method.

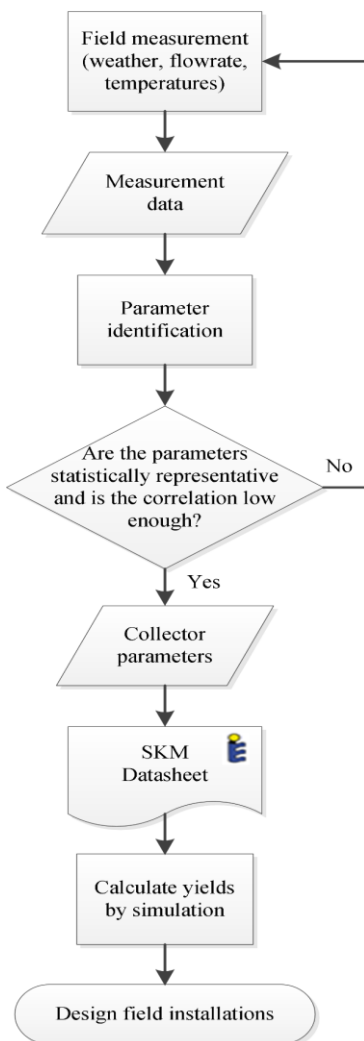


Figure 1: Process diagram of a field certification measurement (ICC method).

Scope and use case

“In-situ certification is targeting but not limited to collectors which because of their size, power output, weight, operating conditions or on-site production can hardly be tested in a laboratory” [9]. The method can therefore be applied to any collector type. The information and results that can be generated with such a measurement are the same as for a certification test in the laboratory. The aim of such a measurement is always a parametrization of the collector, usually for the purpose of obtaining a Solar Keymark certificate. On the basis of the specific parameters, systems can be designed and expected collector yields calculated and compared.

In addition to the above-mentioned reasons for field measurements, the method was also developed against the background that the collector parameters based on laboratory measurements were partly criticized as being not representative in the past. Each manufacturer is now free to have his product tested either in the laboratory or in a field installation, which is, however, associated with increased effort.

Methodology

The collector is measured according to the collector model standardized in ISO 9806 and as far as possible also using the QDT method described there.

In comparison to laboratory measurement, differences in the procedure arise mainly in the following points:

Boundary conditions of the measurement

In order to enable the collector to be measured in regular system operation without interfering with the control system, the boundary conditions specified in the standard, in particular the permissible fluctuation of input

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temperature and mass flow rate as well as the averaging time span used, must usually be adapted. Their influence was investigated in a sensitivity analysis within the framework of the project. Averaging times of 5 minutes worked out for the best results. Very short averaging times or instantaneous data are hardly suitable for this method. With sufficiently long averaging times, fluctuation limits of up to 5K in the input temperature and up to 15% in the mass flow could be allowed and led to good results [10]. All sequences with potential shadowing are excluded from the measurement based on geometrical calculations.

Measurement technology

Deviating from the standard, a SPN1 sensor can be used to measure the diffuse radiation. This comes with the advantage that neither manual adjustment nor a tracking device is needed, hence significantly reducing the maintenance effort and costs. The use of this sensor for global radiation measurement also showed good results in the project with minor deviations compared to standard measurement technology, but is not yet permissible. The use of non-invasive flow rate measurement technology is generally not prohibited by the standard if the corresponding measurement uncertainty is adhered to. However, the project showed that this is only possible under very specific flow conditions and that the application is difficult in most cases. As expected, the use of surface temperature sensors led to large deviations and is therefore not recommended.

Results

In the project ZeKon in-situ it was shown that it is possible to generate parameters for collectors in the field. Slight deviations from the laboratory measurement are within the confidence interval of the reference measurement. This was achieved by using the measurement equipment described above and extended limits for the permissible boundary conditions. In Figure 2 a comparative measurement is shown for an exemplary collector.

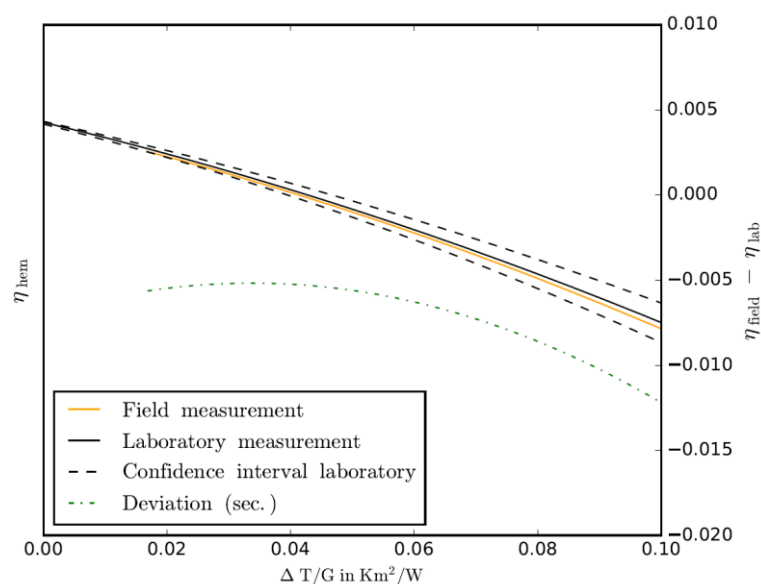


Figure 2: Measurement results from laboratory and field for an exemplary collector of identical design (ICC method).

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A sufficient variance of the measured values with regard to all parameters to be determined is indispensable and not always easy to achieve in the field. This applies in particular to the collector input temperature and, in the case of biaxial collectors, the angle of incidence of both axes. The acquisition and combination of measurement data from more than one collector of a row (at least the very first and last, more if necessary) can be helpful in order to obtain data at different temperature levels. An extrapolation of the efficiency curve is only permissible in the range described by the standard, as applied in Figure 2. It is advisable to precisely analyze the feasible boundary conditions in advance of such a measurement campaign.

Of great importance in such a measurement is the assessment of the parameter quality, which depends to a large extent on the quality of the underlying measurement data. A detailed evaluation of the parameter quality is possible, for example, with the so-called bootstrapping procedure. This involves imposing artificial noise on the data set on the basis of the residuals between the measured and calculated power during parameterization. The residuals of randomly selected measurement sequences from the original data are used to generate a large number of new data sets, which can then be parameterized again. This process is repeated many times and thus a large number of different parameter sets for the collector are generated, whose distribution and co-variances can then be analyzed and used to assess the quality of the parameters [11]. Significant dependencies between different parameters as well as distributions of individual parameters, which deviate strongly from a normal distribution, can indicate an insufficient database. The confidence intervals of the individual parameters also serve as indication for the quality of the evaluation. Tools for the automated application of bootstrapping on the evaluated data have been developed at Fraunhofer ISE and applied within *ZeKon in-situ*.

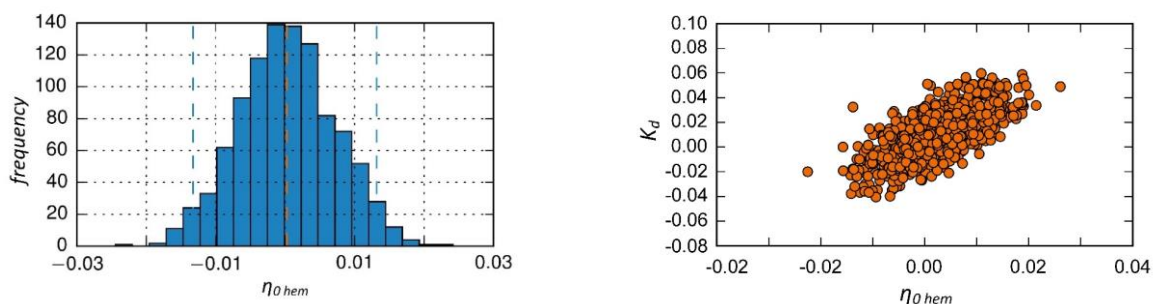


Figure 3: Exemplary graphs for parameter distribution (left) and covariance (right) from bootstrapping (ICC method).

Figure 3 shows two exemplary graphs resulting from bootstrapping to demonstrate how it helps to assess the parameter quality. On the left side the distribution of $\eta_{0,hem}$ (normalized to the originally determined parameter value) for an exemplary field measurement is presented. The dotted orange line marks the median value and the blue dotted lines represent the 95% confidence interval. In this case the confidence interval of the conversion factor ($\eta_{0,hem}$) is close to what is typical for a laboratory measurement. In combination with the nearly normal distribution it indicates that the underlying data basis allows a meaningful non-biased determination of the parameter.

On the right side of Figure 3 an example for the covariance between $\eta_{0,hem}$ and K_d is shown (normalized to the originally determined parameter values). It indicates a clear correlation of high values for $\eta_{0,hem}$ with high

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values for K_d , meaning that on basis of the underlying data set both parameters could not be identified completely independent. The strength of a correlation can be measured by the correlation coefficient, which can range from 0 (fully independent) to 1 (fully dependent) and is 0.7 in this example. A result like this implies the requirement for further assessment of sufficient variability in the measurement data. This mathematical data point evaluation is most helpful to have un-biased collector parameters for different products from field measurement, without the need of a new model.

Dynamic Collector Array Test (D-CAT)

Introduction

The Dynamic Collector Array Test (D-CAT) is an in situ test method for quality assessment of large collector arrays under fully dynamic operating conditions. The method has a similar physical modeling approach for single collectors as the quasi-dynamic test procedure of ISO 9806, but extends the ISO model to collector rows and collector arrays. A proof of concept of the method has been developed in the Austrian funded research project *MeQuSo* [7].

Scope and use case

The D-CAT method uses a parameterized collector array model which is applicable to typical array configurations of large-scale solar thermal plants. In the current state of development, the D-CAT method is limited to arrays with flat plate collectors, although extensions to other collector types are possible within the existing framework.

The main goal of the method is to obtain a set of parameters of this model to characterize the behavior of the collectors based on measured operating data. The model accepts fully dynamic inputs and can thus be applied to fully dynamic conditions of the normal plant operation. That is, the method does not require running special test sequences or pre-filtering data to obtain “quasi-dynamic” states. A central feature of the D-CAT method is the fact that it can be run in automated mode and therefore repeated in time with little additional effort.

Performance reductions that concern the collectors on a component level (such as soiling, broken insulation, faulty foil tension etc.) are reflected in the estimated parameters to obtain a characterization of the collectors under ‘real-world’ conditions [12]. Heavily soiled collectors will have worse values for the optical parameters than clean collectors. On the contrary, performance relevant factors which do not accrue from the collector on a component level (such as local weather conditions, operating conditions, collector array geometry, hydraulic setup, etc.) are not mirrored in the estimated parameters. A collector array operated at higher temperatures will have a lower efficiency, but the same collector parameters as an array operated at lower temperatures.

The in situ parameterization of a collector array can be used as follows:

- commissioning: target/actual comparison with guaranteed thermal power output/yield
- surveillance: detecting trends with repeated testing

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- control: parametrization of collector array models
- testing at different locations: transparent comparison of collector arrays

Methodology

The flowchart in Figure 4 shows the process of the method.

Performance boundaries

The performance boundary is the collector array including the collectors and connection pipes between the collectors (Figure 8). Not included are the distribution pipes from the array to the heat exchanger.

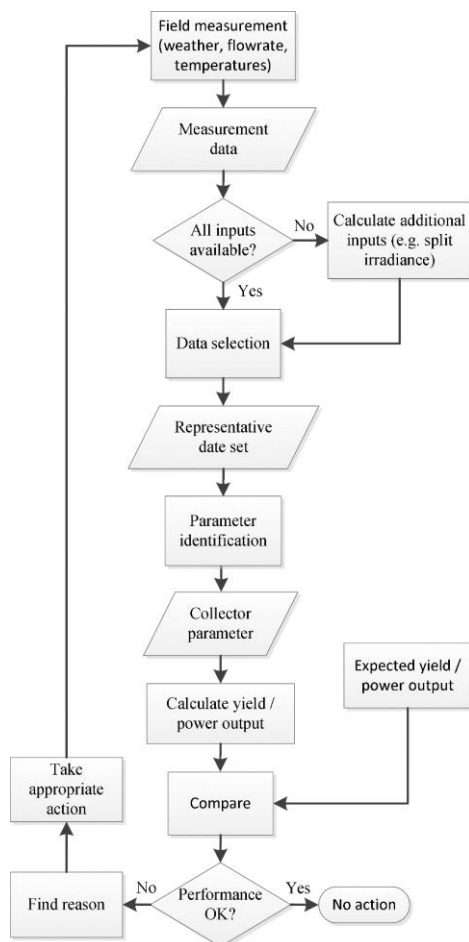


Figure 4: Flowchart for processing the Dynamic Collector Array Test (D-CAT) method.

Modeling

A one-node model (fluid temperature node) and two-node model (fluid and solid temperature nodes) can be used. Both models take into account that collector rows are relatively long in large arrays, so the temperature is assumed to change depending on the position along the fluid direction. The partial differential equations (PDE) for a specific position are given below:

One-node model:

$$\dot{m}_{pri} c_{f,x} \frac{\partial \vartheta_{f,x}}{\partial x} = \eta_{0,b} K_b(\theta) \cdot s \cdot G_b + \eta_{0,b} K_d G_{d,avg} - a_1(\vartheta_{f,x} - \vartheta_a) - a_2(\vartheta_{f,x} - \vartheta_a)^2 - a_5 \left(\frac{\partial \vartheta_{f,x}}{\partial t} \right)$$

Two-node model:

$$\dot{m}_{pri} c_{f,x} \frac{\partial \vartheta_{f,x}}{\partial x} = b_0(\vartheta_{s,x} - \vartheta_{f,x}) - c_{f,A,x} \left(\frac{\partial \vartheta_{f,x}}{\partial t} \right) \quad (\text{eq. 1})$$

$$b_0(\vartheta_{s,x} - \vartheta_{f,x}) = (\tau\alpha) K_b(\theta) \cdot s \cdot G_b + (\tau\alpha) K_d G_{d,avg} - b_1(\vartheta_{s,x} - \vartheta_a) - b_2(\vartheta_{s,x} - \vartheta_a)^2 - b_5 \left(\frac{\partial \vartheta_{s,x}}{\partial t} \right) \quad (\text{eq. 2})$$

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The modeling has the following distinct features:

- The explained variable of the model equations is not the thermal power output like in ISO 9806, but the measured outlet temperature and additional temperatures within the collector array which are not measured (grey-box model).
- Fluid propagation (transport) is modelled in the spatial derivative terms. While this increases the model complexity, it is a crucial feature especially for estimating the collectors' heat capacity because travel times of the fluid through the array is oftentimes comparable to the collectors' time constant [13].
- For collectors within an array, sky and ground view are obstructed due to collectors placed in front [14]. This reduces the diffuse irradiance along the collector height from top to bottom. The D-CAT method calculates an average diffuse irradiance which corrects for this effect. For laboratory tests, there is no view obstruction, and a correction of the measured irradiance at the top of the collector is not necessary.
- Contrary to ISO 9806, wind heat losses are not included in the model, as the wind speed above the collector cannot be representatively measured for collector arrays. For collectors with high wind heat losses, data with high wind speed should be discarded.
- Operating conditions with internal shading can be included if the share of the collector array which is shaded can be determined with reasonable accuracy and the shading share is low. But it is not recommended as a general rule, as it could add more uncertainty to the parameter estimation. As a standard, only conditions with no internal shading are used.
- The two-node model is typically substantially superior in explaining dynamic behavior, but it lacks direct comparability with the quasi-dynamic ISO 9806 parameters. It is recommended to use the two-node model when the residuals of the transient collector array operating conditions are large.

The model equations have no analytical solution. They are solved numerically based on the method of lines: The temperatures are discretized in flow direction based on a one-dimensional finite volume method [15]. This results in a system of ODEs which can be efficiently solved by appropriate stiff ODE solvers. This approach calculates all heat transfers based on the local temperature of each finite volume segment. For the one-node model, this leads to the same collector parameters as in the ISO 9806 equation.

Measurement setup and data acquisition

Since D-CAT is a method taking into account fully dynamic behavior, it requires relatively high sampling rates of not more than 1 minute and ideally 10 seconds or less. The required inputs that are used for the parameter estimation are the mass flow rate of the collector array, the return and flow temperature at the entry and exit points to the collector array, the total irradiance in the collector plane (or any other surface) and the heat capacity of the fluid. The method contains an advanced radiation processing algorithm which splits the total radiation in its direct and diffuse part (if only the hemispherical radiation is measured). Other

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measurement setups are possible. In these cases, a simulation procedure is used to calculate the model inputs at the performance boundaries.

Data processing and performance assessment

A key part of the D-CAT method is the data selection, which is done in three steps:

1. Only include data where the model is applicable. All operating conditions above a minimal thermal power output level and where no internal shading and external shading occurs can be used. Variable volume flows and rapid return temperature changes (typical when using speed-controlled pumps) are acceptable.
2. Intervals with 90 minutes of continuous operation are retrieved/selected.
3. Typically, some type of intervals (e.g. intervals with high irradiance and constant operation temperatures during the summer months) are overrepresented, which can lead to overfitting and high correlation of the parameters. To address this problem, a subset of (typically around 20) optimal intervals is selected automatically, where each interval makes a substantial contribution to determine the model parameters. This can be interpreted as an optimal design problem, where the total interval information is maximized by maximizing the determinant of the Fisher information matrix (D-optimality criterion) [16].

Based on the retrieved intervals, the parameter estimation is done by minimizing a cost function, the RMSE of the deviation between measured and simulated array outlet temperatures. The simulation of an interval requires knowing the initial conditions (the temperatures of the finite volume segments) which are not measured. To overcome this problem, the first 30 minutes of an interval are used for a pre-simulation to get a good assumption of the initial conditions for the simulation of the main 60-minutes-intervals.

Results

The D-CAT method allows an in situ parameterization of the collectors in the collector array (such as zero loss efficiency, heat loss coefficients, thermal capacity, etc.). Figure 5 shows typical results for the efficiency and incidence angle modifier curves when a collector array is tested at inauguration and after multiple years of operation. For each test run, different parameter values (“in situ parameters”) are obtained which mirror the current state of the collectors. For this collector array, the performance of the collectors at inauguration is a bit below the datasheet. The performance is further reduced after multiple years of operation. Changes in the characteristic collector parameters can indicate problems like degradation of the insulation [17]. A thermal power output guarantee can be checked by comparing the thermal power output/efficiency based on datasheet parameters versus in situ parameters for defined operating conditions. A yield guarantee can be checked by comparing the simulated solar yield with the data sheet parameters versus in situ parameters.

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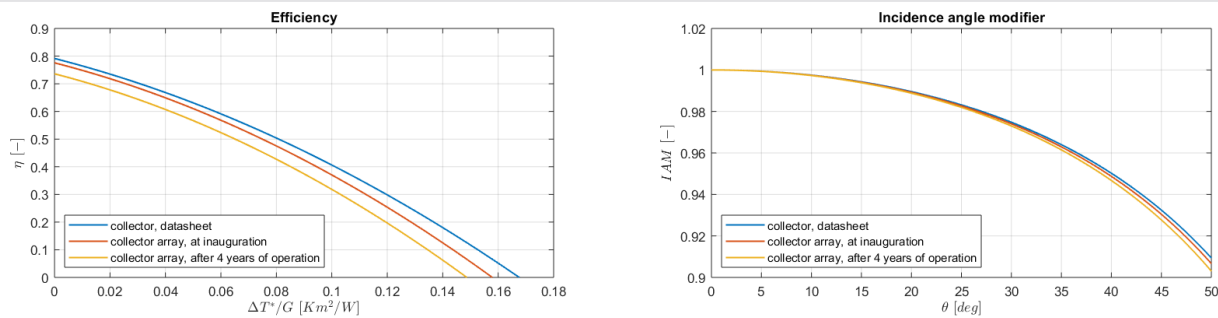


Figure 5: Efficiency and incidence angle modifier curves with datasheet versus in situ parameters (D-CAT method).

Performance Check for Collector Arrays (PC) - ISO/TC 180 work item

Introduction

This Performance Check (PC) method - or similar - has been used in Denmark for approx. 10 years to check performance of large-scale solar collector fields for district heating. It was described in fact sheets in IEA SHC Task 45 [18], [19]. It has now been proposed as an input to a new ISO standard, and a working group under ISO/TC180 is elaborating this standard right now. The description below gives present status, the final standard may derive.

Scope and use case

This method can be used for a simple check of the collector field power performance. It can be used in connection with the commissioning of the collection field and/or for continuous on-line surveillance. It can be used for flat plate collectors and for concentrating collectors.

Methodology

The overall principle is to check the measured power against the estimated power when the collector field is running close to full power.

Calculating estimated power

The estimated power is calculated based on collector parameters from ISO 9806 testing plus some safety factors.

The equation used for estimating the collector field power is chosen depending on collector type and the wanted uncertainty level. Three equations are available:

Equation A: A simple power performance estimate for non-concentrating collectors:

$$\dot{Q}_{\text{sec,est}} = n_{\text{col}} \cdot A_G \cdot [\eta_{0,\text{hem}} G_{\text{hem}} - a_1 (\vartheta_{\text{m,cf}} - \vartheta_a) - a_2 (\vartheta_{\text{m,cf}} - \vartheta_a)^2 - a_5 (d\vartheta_{\text{m,cf}}/dt)] \cdot f_{\text{safe}} \quad (\text{eq. A})$$

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Equation B: A more advanced equation for non- or low-concentrating collectors (concentration ratio $C_R < 20$) can be used if the direct and diffuse radiation on the collector plane is available. Using eq. B will normally give results with smaller uncertainty than using eq. A as incidence angle modifiers for the collector are considered in eq. B:

$$\dot{Q}_{\text{sec,est}} = n_{\text{col}} \cdot A_G \cdot [\eta_{0,b} K_b(\theta_L, \theta_T) G_b + \eta_{0,b} K_d G_d - a_1 (\vartheta_{m,cf} - \vartheta_a) - a_2 (\vartheta_{cf,m} - \vartheta_a)^2 - a_5 (d\vartheta_{m,cf}/dt)] \cdot f_{\text{safe}} \quad (\text{eq. B})$$

Equation C: Is used for concentrating collectors with high concentration ratio $C_R \geq 20$ – tracking in one or two axis and utilizing mainly or only the direct radiation.

$$\dot{Q}_{\text{sec,est}} = n_{\text{col}} \cdot A_G \cdot [\eta_{0,b} K_b(\theta_L, \theta_T) G_b - a_1 (\vartheta_{m,cf} - \vartheta_a) - a_5 (d\vartheta_{m,cf}/dt) - a_8 (\vartheta_{m,cf} - \vartheta_a)^4] \cdot f_{\text{safe}} \quad (\text{eq. C})$$

f_{safe} is taking into account pipe and other heat losses, measurement uncertainty and other uncertainties.

To limit uncertainties, some restrictions on the operations conditions are given: No shadows; moderate change in collector mean temperature; no risk of snow/icing; no high wind – and if eq. A is used: incidence angle $< 30^\circ$. Only measurement points which satisfy these restrictions are valid.

Power measurement

Although the performance is checked for the primary loop, it is recommended to measure the power output on the secondary side to avoid uncertainties due to the physical values of the collector loop fluid. So, collector field power \dot{Q}_{sec} shall be measured on the secondary side of the heat exchanger, based on flow and temperature measurements:

$$\dot{Q}_{\text{sec}} = \dot{V}_{i,\text{sec}} \cdot \rho_{i,\text{sec}} \cdot c_{f,\text{sec}} \cdot (\vartheta_{e,\text{sec}} - \vartheta_{i,\text{sec}})$$

The flowchart in Figure 6 below shows the process of the method.

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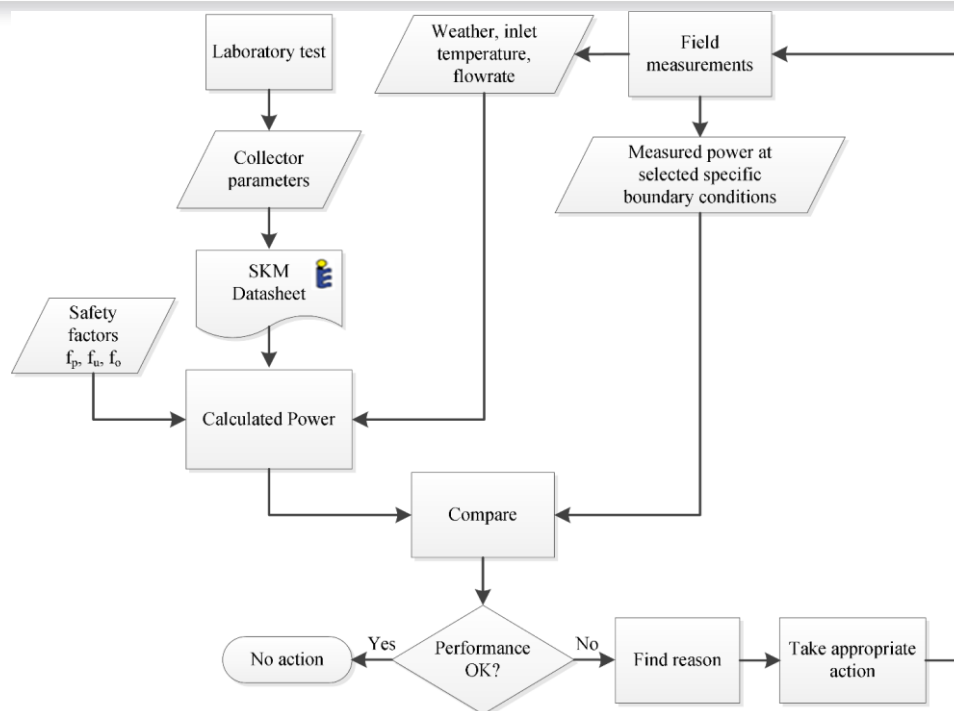


Figure 6: Flowchart for processing the Performance Check (PC) method.

Measurement equipment

The necessary measurement equipment for measuring the collector field power output is indicated in Figure 8.

The equipment for solar irradiance measurement follows from the equation used:

- Eq. A: Global irradiance measurement in the collector plane is needed.
- Eq. B: Direct and diffuse irradiance measurement is needed, options are:
 - Pyranometer for global irradiance in the collector plane + pyranometer with shadow ring for diffuse irradiance in the collector plane
 - Pyranometer for global irradiance in collector plane + pyrhemliometer for beam irradiance
- Eq. C: Only pyrhemliometer for beam irradiance is needed.

Other equipment:

- Energy meter (flow meter + temperature sensors in secondary (water) loop)
- Temperature sensors for in- and outlet of heat exchanger primary loop
- Temperature sensor for ambient air temperature
- Anemometer for wind velocity

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Logging / recording

Measurement data are logged (and calculated) at least each minute. Averaged data are recorded (at least) each hour.

Uncertainty levels

Present version of the method has two levels of uncertainty – first level corresponds more less to the ISO 9806 uncertainty level, second level is more relaxed.

Results

The main final result is the deviation between summarized estimated and summarized measured performance given as a percentage:

Deviation in \dot{Q} :

$$d\dot{Q}\% = (\dot{Q}_{\text{sec}} - \dot{Q}_{\text{sec,est}}) / \dot{Q}_{\text{sec}}$$

Supplementary results are presented in Figure 7, showing the measured data points for power output against the corresponding estimated power on the left side and the average measured and estimated power on the right.

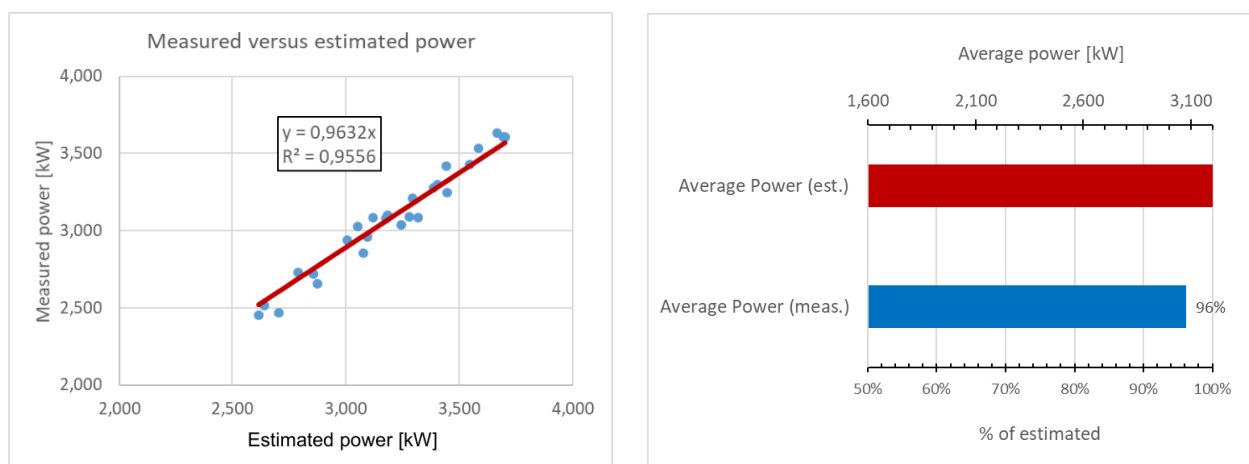


Figure 7: Measured points of power versus estimated points of power (left) and average measured power versus average estimated power (right) for PC method.

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Comparison of methodologies

Measurement setups

The system layout with sensor locations and performance measurement boundaries for all three methodological approaches is shown in Figure 8.

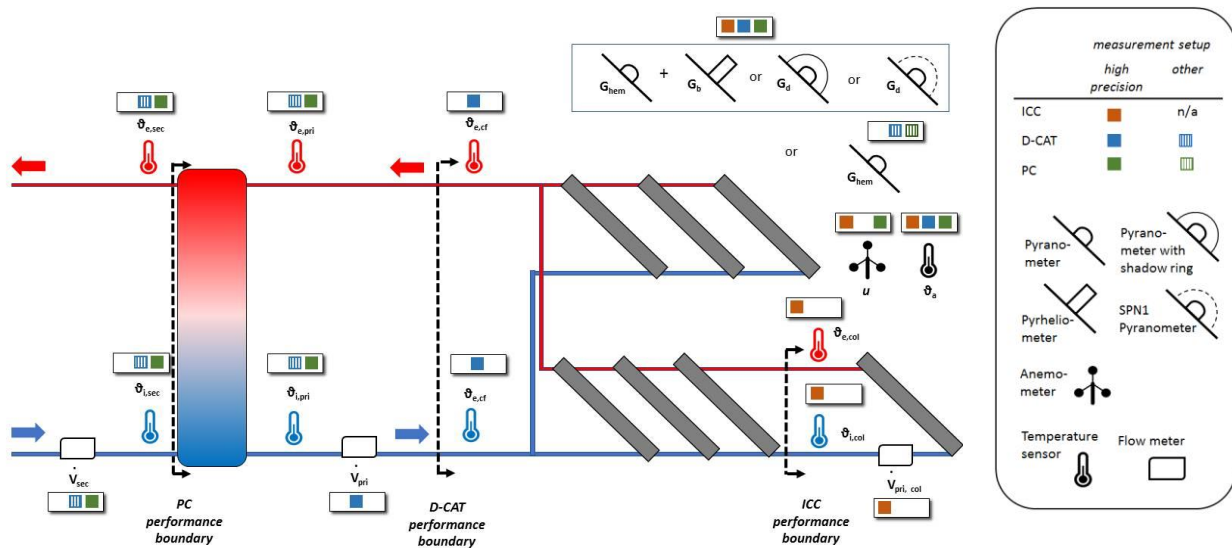


Figure 8: System layout, sensor locations and performance boundaries.

While the ICC method generates collector parameters from measurement data taken directly at (one or more) single collectors, the D-CAT method takes measurement data from the complete collector field (excluding distribution pipes) and uses a collector field model with correction terms for different factors influencing the field to derive collector parameters. The PC method refers to the complete field including the distribution pipes and recommends measuring the power output in the secondary loop.

Distinguishing features

To give an overview of the differences between the described methods, their distinctive properties are summarized in Table 1.

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Table 1: Distinctive features of the test methods.

| Test procedure | ISO 9806 <i>Laboratory testing</i> | ICC <i>In situ Collector Certification</i> | D-CAT <i>Dynamic Collector Array Test</i> | PC <i>Performance Check for Collector Arrays</i> |
|---|--|---|--|---|
| Basics | | | | |
| <i>Use case (main)</i> | collector certification | collector certification, evaluating single collectors in field installation | performance check and surveillance based on in situ collector array parametrization under fully dynamic conditions | performance check under stable conditions close to full power operation, surveillance |
| <i>Test site</i> | laboratory | In situ | In situ | In situ |
| <i>Test object (performance measurement boundaries)</i> | single collector | single collector(s) | collector array without pipes | collector array including pipes and heat exchanger |
| <i>Collector types</i> | all | all | flat plate; extensions to other collector types possible | all |
| <i>Status</i> | standard | permissible; Annex P5.5 of Solar Keymark Scheme Rules | proof of concept completed | input to standardization work item in ISO TC 180 |
| Test outcome | | | | |
| <i>Key performance indicators</i> | normative collector parameters | normative collector parameters | collector parameters describing the measured behavior of the collectors in the array | target/actual comparison based on ISO 9806 data sheet parameters |
| <i>Solar yield estimation</i> | ✓ | ✓ | ✓ | × |
| Model | | | | |
| <i>Explained variable</i> | thermal power output | thermal power output | outlet temperature | thermal power output |
| <i>Collector model</i> | steady state, quasi-dynamic | quasi-dynamic (ISO 9806) | dynamic model resulting in ISO 9806 parameters; additional 2-node model | three equations based on collector types (used for target performance) |

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| | | | | |
|---|---|---|---|--|
| | | | | comparison, but not parameter estimation) |
| <i>Additional collector array modelling</i> | - | - | effective direct and diffuse radiation, distribution pipes, heat exchanger (depending on sensors) | reduction factors for distribution pipes and heat exchanger losses |
| Measurement setup, data processing | | | | |
| <i>Required sensors</i> | standard high precision sensors | standard high precision sensors, alternative sensors for diffuse irradiance measurement allowed | irradiance, air temperature, fluid temperatures, volume flow; low precision sensors possible | irradiance, air temperature, wind velocity, fluid temperatures, volume flow |
| <i>Duration of measurement</i> | 4-5 days | minimum 5-10 days, up to 6 months (depending on collector type and operation conditions) | minimum 4-5 days, up to 6 months (depending on operation conditions) | minimum 4-5 days, up to 6 months (depending on operation conditions) |
| <i>Test data</i> | defined test sequence | normal plant operation | normal plant operation | normal plant operation |
| <i>Main boundary conditions</i> | strict limits especially regarding inlet temperature and mass flow rate stability | extended limits for inlet temperature and mass flow rate stability; no shading, no high wind | no external shading; internal shading allowed in some circumstances; minimum 90 minutes of continuous operation | no shadows; moderate change in collector mean temperature; no risk of snow/icing; no high wind – and if eq. A is used: incidence angle < 30° |
| <i>Sampling rate / Averaging time</i> | < 10s / no specifications | < 10s / multiple times the pass-through time of fluid through collector recommended | ≤ 1 min / 10s for data with sampling rate < 10s, otherwise not necessary | ≤ 1 min / 15 – 60 min |
| <i>Requirements for data handling</i> | spread sheet | spread sheet, additional software tools for automated plausibility checks and analysis of parameter quality recommended | programming skills required (e.g. Python, R, MATLAB®), but test can be completely automated | spread sheet |

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Measurement information and purpose

Figure 9 shows, in a simplified schematic way, the information provided by the methods and the requirements for which they are designed.

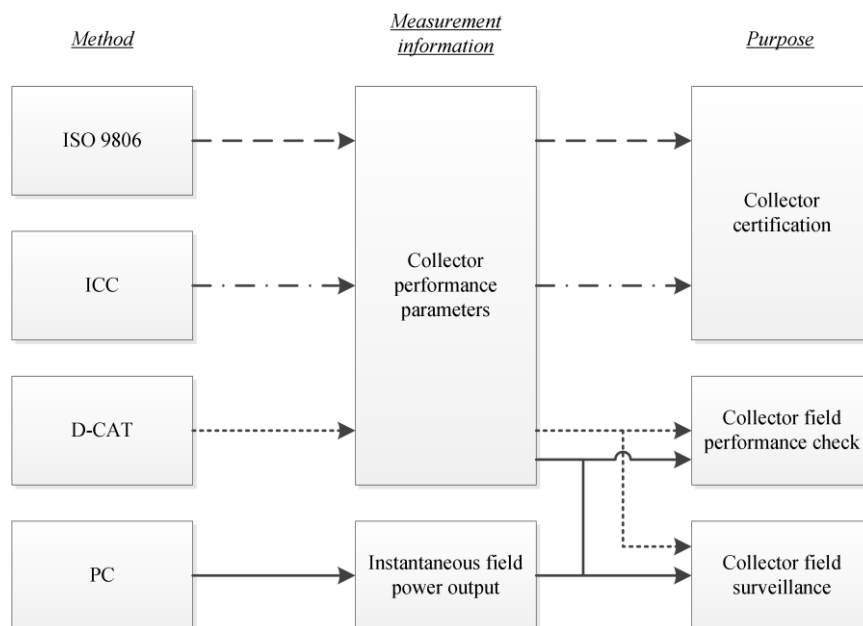


Figure 9: Measurement purposes versus applicable methods.

Discussion and conclusion

While all three methods are generally based on the collector models of ISO 9806, they differ with regard to the measurement boundaries, the permissible and required data basis, calculation methods and associated computational effort, as well as the required sensor technology (see Table 1). There are differences in the parameters used within the methods, interpreting and processing the ISO 9806 in different ways.

The different methods were developed for different application purposes and therefore deliver dissimilar results with varying or selectable uncertainty levels, which are not analyzed in detail yet. Thus, they neither compete with nor contradict each other, but may even complement each other. It is therefore important for manufacturers, planners and operators of plants to first define the objectives of a measurement campaign, the expected information and accuracies as well as acceptable time and cost effort precisely before deciding on a procedure.

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Appendix

| Symbol | Description | Unit |
|-------------|--|---------------------|
| A_G | Gross area of collector as defined in ISO 9488 | m^2 |
| a_1 | Collector heat loss coefficient at $(\vartheta_{m,col} - \vartheta_a) = 0$ | $W/(m^2 \cdot K)$ |
| a_2 | Temperature dependence of collector heat loss coefficient | $W/(m^2 \cdot K^2)$ |
| a_3 | Wind speed dependence of the collector heat loss coefficient | $J/(m^3 \cdot K)$ |
| a_4 | Sky temperature dependence of the collector heat loss coefficient | - |
| a_5 | Effective thermal capacity of the collector | $J/(m^2 \cdot K)$ |
| a_6 | Wind speed dependence of the zero loss efficiency of the collector | s/m |
| a_7 | Wind speed dependence of IR radiation exchange of the collector | $W/(m^2 \cdot K^4)$ |
| a_8 | Radiation losses of the collector | $W/(m^2 \cdot K^4)$ |
| b_0 | Heat transfer coefficient from solid part to fluid at $(\vartheta_{s,x} - \vartheta_{f,x}) = 0$, based on gross collector area | $W/(m^2 \cdot K)$ |
| b_1 | Heat loss coefficient from solid part to ambient at $(\vartheta_{s,x} - \vartheta_a) = 0$, based on gross collector area | $W/(m^2 \cdot K)$ |
| b_2 | Temperature dependence of heat loss coefficient from solid part to ambient, based on gross collector area | $W/(m^2 \cdot K)$ |
| b_5 | Effective thermal capacity of solid part of the collector (not including the fluid), based on gross collector area | $J/(m^2 \cdot K)$ |
| $C_{f,A,x}$ | Heat capacity of heat transfer fluid per square meter gross collector field area at position x in the collector field | $J/(kg \cdot K)$ |
| $C_{f,sec}$ | Specific heat capacity of heat transfer fluid (water) at heat exchanger mean temperature | $J/(kg \cdot m^2)$ |
| $C_{f,x}$ | Specific heat capacity of heat transfer fluid at position x in the collector field | $J/(kg \cdot K)$ |
| E_L | Longwave irradiance ($\lambda > 3 \mu m$) | W/m^2 |
| f_{safe} | Safety factor for Performance Check (PC) method, taking into account pipe and other heat losses, measurement uncertainties and other uncertainties | - |
| G_b | Direct solar irradiance on collectors | W/m^2 |
| G_d | Diffuse solar irradiance, measured at the top of the collector | W/m^2 |
| $G_{d,avg}$ | Modelled average diffuse solar irradiance on the collectors, accounting for the obstructed sky and ground view for collectors within the array | W/m^2 |
| G_{hem} | Hemispherical solar irradiance, measured at the top of the collector | W/m^2 |

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| | | |
|---------------------------|--|-------------------------------------|
| $K_b(\theta)$ | Incidence angle modifier for direct solar irradiance with one incidence angle (for flat plate collectors) | - |
| $K_b(\theta_L, \theta_T)$ | Incidence angle modifier for direct solar irradiance with longitudinal and transversal angle | - |
| K_d | Incidence angle modifier for diffuse radiation | - |
| \dot{m}_{pri} | Mass flow on primary side | kg/s |
| n_{col} | Number of collectors in the collector array | - |
| \dot{Q}_{sec} | Thermal power supplied from heat exchanger | W |
| $\dot{Q}_{sec,est}$ | Estimated thermal power of collector field, supplied at heat exchanger on secondary side | W |
| \dot{Q}_{col} | Useful power extracted from collector | W |
| s | Share of collector area with no shading of direct solar irradiance | - |
| t | Time | s |
| u | Surrounding air speed | m/s |
| u' | Reduced surroundings air speed ($u' = u - 3$ m/s) | m/s |
| $\dot{V}_{i,col}$ | Volume flow for a single collector | m ³ /s |
| $\dot{V}_{i,pri}$ | Volume flow at heat exchanger inlet on primary side | m ³ /s |
| $\dot{V}_{i,sec}$ | Volume flow at heat exchanger inlet on secondary side | m ³ /s |
| x | Axial coordinate for collector field model along the flow direction of the fluid | m |
| $\eta_{0,b}$ | Peak collector efficiency ($\eta_{0,b}$ at $\vartheta_{m,col} - \vartheta_a = 0$ K) based on beam irradiance G_b | - |
| $\eta_{0,hem}$ | Peak collector efficiency ($\eta_{0,hem}$ at $\vartheta_{m,col} - \vartheta_a = 0$ K) based on hemispherical irradiance G_{hem} | - |
| $(\tau\alpha)$ | Effective transmittance-absorptance product | - |
| θ | Angle of incidence | degrees |
| θ_L | Longitudinal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the longitudinal plane | degrees |
| θ_T | Transversal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the transversal plane | degrees |
| ϑ_a | Ambient air temperature | °C |
| $\vartheta_{s,x}$ | Solid part temperature at position x in the collector field | °C |
| $\vartheta_{f,x}$ | Fluid temperature at position x in the collector field | °C |
| $\vartheta_{i,cf}$ | Return (inlet) temperature of collector field, measured after the distribution pipes | °C |
| $\vartheta_{i,col}$ | Return (inlet) temperature of a single collector | °C |
| $\vartheta_{i,pri}$ | Heat exchanger inlet temperature, measured in primary loop at heat exchanger inlet | °C |
| $\vartheta_{i,sec}$ | Heat exchanger inlet temperature, measured in secondary loop at heat exchanger inlet | °C |
| $\vartheta_{e,cf}$ | Flow (outlet) temperature of collector field, measured before the distribution pipes | °C |
| $\vartheta_{e,col}$ | Flow (outlet) temperature of a single collector | °C |
| $\vartheta_{e,pri}$ | Heat exchanger outlet temperature, measured in primary loop at heat exchanger inlet | °C |
| $\vartheta_{e,sec}$ | Heat exchanger outlet temperature, measured in secondary loop at heat exchanger outlet | °C |
| $\vartheta_{m,cf}$ | Mean temperature of heat transfer fluid for collector field | °C |
| $\vartheta_{m,col}$ | Mean temperature of heat transfer fluid for collector | °C |
| $\rho_{i,pri}$ | Density of heat transfer fluid at heat exchanger inlet temperature on primary side | kg/ m ³ |
| $\rho_{i,sec}$ | Density of heat transfer fluid (water) at heat exchanger inlet temperature on secondary side | kg/ m ³ |
| s | Stefan-Boltzmann constant | W/(m ² ·K ⁴) |