In-situ Testing of Large Collector Arrays – Challenges and Methodological Framework

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Abstract

In this paper, the major challenges of in-situ collector array testing are analyzed and a framework to address them is developed. The study of the challenges is based on theoretical investigations as well as on data evaluations of a solar district heating (SDH) plant which was equipped with high-precision measurement equipment.

Keywords: in-situ testing, collector array, in-situ measurement, large solar thermal plants, solar district heating

1. Introduction

1.1 The need for in-situ testing of large scale solar thermal plants

Large scale solar thermal plants (>500 m² collector area, >350 kW_{th} nominal thermal power) are a cost-effective way to provide renewable heat (ESTIF, 2015). The market has experienced considerable growth recently, with close to 500,000 m^2 of solar collectors (350 MW_{th}) installed in large scale systems in Europe in 2016. 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}) started operating in December 2016 (Weiss, Spörk-Dür and Mauthner 2017).

Key factors to increase the market penetration of large solar thermal plants are the reduction of investment risks and the realization of cost saving potentials during the plant operation by means of performance guarantees (for the thermal power output and/or solar yield), efficient monitoring and ongoing optimization.

These measures rely on an accurate and reliable assessment and characterization of the collector array performance for the observed operational behavior. To this aim, an in-situ test procedure to evaluate the thermal power output of large collector arrays under transient conditions is developed. Hereafter we refer to this procedure as the in-situ collector array test.

1.2 In-situ collector array test

The cornerstones of the test procedure are the following:

- focusing on large scale collector arrays with flat plate collectors (flat plate collectors are the most common collector technology deployed in large scale applications)
- the outcome of the test is a characterization of the thermal power output with a set of characteristic parameters which are estimated from measurement data, using a parametrized model of the collector array
- the test considers 'real operation conditions' like soiling, shading, etc. which affect the collector array performance (for single collectors under laboratory conditions, these 'disturbances' can be controlled or are not relevant)
- applicability of the procedure to the most common plant configurations and measurement setups
- the system boundaries of the collector array model are the return and supply lines on the primary side of the heat exchanger (or the equivalent position if there is no heat exchanger)
- the modeling of the collector array puts emphasis on the most important influencing factors on the thermal performance, but restrains from a detailed representation to facilitate the application of the procedure

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- a major requirement is a short test period and the reliance on data from the normal plant operation whenever possible
- provision of a standardized and traceable framework for data acquisition, data processing and parameter estimation

The in-situ test procedure will have some similarities with the ISO 9806 standard for single collector tests, but focuses on large collector arrays instead of single collectors and moves from laboratory to 'real-world' conditions. The aim is not to test single collectors in the field, but rather to examine the behavior of an 'average collector' within the array arrangement. In-situ testing of collector arrays is also useful when single collector tests are very difficult to implement, e.g. for large collectors assembled directly at the construction site.

Work on using in-situ data to determine collector (array) parameters date back more than twenty years and include Perers (1993), Bosanac and Nielsen (1997) and Spirkl et al. (1997). These approaches are based on the modeling and data evaluation techniques of single collectors in the spirit of EN 12975. In later work, approaches to identify the collector (array) parameters based on dynamic system simulations were also used (see e.g. Almeida et al. (2014)). In the literature, there is no methodologically sound procedure for testing large collector arrays available.

1.3 Content and structure of this work

In this paper, the major challenges of in-situ collector array testing are analyzed and a framework to address them is developed. The study of the challenges is based on theoretical investigations as well as on data evaluations of a solar district heating (SDH) plant which was equipped with high-precision measurement equipment. To develop an in-situ collector array test, reliable data of large scale installations are essential.

The structure of the paper is as follows. In chapter 2, the main steps of the in-situ collector array test are outlined with the help of a flowchart. In chapter 3, the measurement setup of the SDH plant which was used to gain measurement data for the development of the methodology is shown. In chapter 4, the challenges of the test procedure are analyzed in detail. In chapter 5, a framework to address these challenges is presented. Chapter 6 summarizes the results and gives an outlook on future work.

2. Flowchart of the in-situ collector array test

Fig. 1 shows a simplified flowchart of the collector array test. The first steps are to create a model of the solar thermal plant and to collect, pre-process, select and assess the measurement data. Based on these preliminary tasks, the model input data, i.e. the time series with the explanatory variables and the dependent variable which enter the parameter estimation procedure, are created. The parameters are then estimated and a test report is issued.

[A] Plant representation

The representation of the solar thermal plant is done by adapting a general modeling approach which is suitable for the most common configurations. The representation encompasses the (i) typical collector array parameters (gross collector area, total fluid content, etc.), (ii) collector array geometry (row spacing, azimuth and tilt angle of the collectors, etc.) which is necessary for the irradiance modeling, (iii) hydraulic arrangement and (iv) information on the measurement setup (type of sensors, sensor positions, sensor precisions, installation conditions, sampling rate, …) and available data.

[B.1] Measurement data acquisition and data pre-processing

For commercial installations, the quality of the measurement data is almost always an issue. The measurement data needs to be checked for missing values, sensor readings outside physically plausible ranges, synchronization problems of the data logger, etc. Redundancies of the measurement setup (e.g. both beam irradiance, diffuse irradiance and total irradiance are measured) can be used for additional inspections. An often used check for in-situ collector array testing is to compare the daily sum of the global irradiance and the daily collector yield and verify if the relationship is approximately linear (Perers 1993).

[B.2] Measurement data selection

After pre-processing we have validated data. The next step is to select specific intervals to be used in the subsequent parameter estimation procedure. For example, data when there is no volume flow in the collector array might be excluded. If there is a lot of data available, it can be necessary to cluster the data and reduce it to ‘characteristic days’ with typical operational and ambient conditions to obtain a representative sample.

[B.3] Test data assessment

The test data needs to meet certain criteria, and these have to be checked before applying the parameter estimation procedure. Crucial is a sufficient variation, especially of the irradiance and the return temperature, as well as a limited correlation of the explanatory variables (e.g. test data with low irradiance values and low and high temperatures as well as high irradiance values and low and high temperatures).

[C] Model input data

The test data is then transformed to the explanatory variables and the dependent variable of a general collector array model, which yields the same core parameters for all arrays. The explanatory variables include for example (i) the beam irradiance on the tilted collectors calculated from the DNI measurement, the position of the sun and the collector orientations and (ii) the primary volume flow, derived from the return and flow temperatures and fluid properties of the primary side and the power output measurement of the secondary side. This allows some flexibility regarding the measurement setup. Oftentimes, the model input data are exactly the same as the test data. As long as the transformation from the test data to the model input data does not depend on the estimated parameters itself, the transformed variables can be treated like measured values, but with additional modeling and measurement uncertainties.

[D] Parameter identification

The next step is the parameter identification which yields the collector array parameters (heat losses coefficients, incidence angle modifier, etc.). As the collector array model is based on differential equations, a dynamic parameter estimation procedure is needed. For each set of parameters, a time series for the predicted output values is calculated and the parameters are chosen in such a way, that the mean prediction error (predicted output values minus measured output values) is minimized.

[E] Test report

The final step is the documentation of the results in a test report. The documentation contains the obtained parameters, their significance, uncertainties, etc. and descriptions of the plant representation, measurement data, data selection, etc.

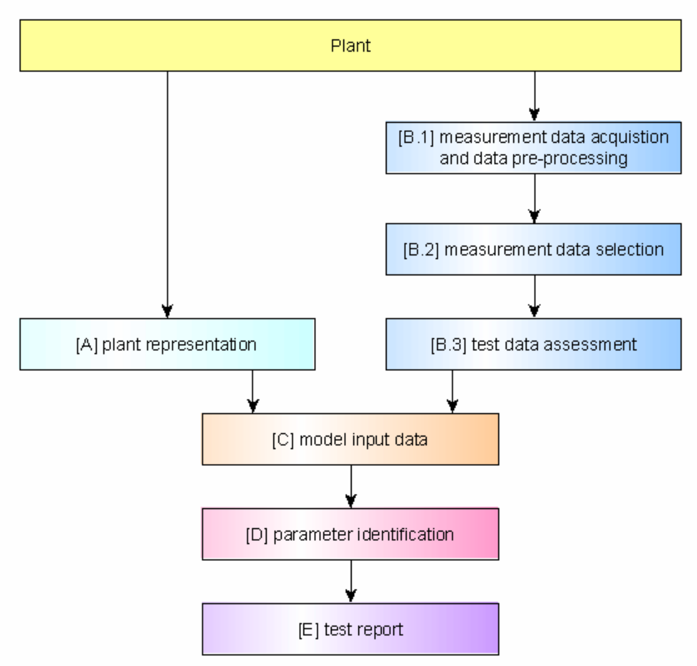

Fig. 1: Flowchart of the in-situ collector array test

3. High-precision measurement of a SDH plant

A cornerstone to develop the in-situ collector array test is the availability of high-precision measurement data of large solar thermal plants. To this aim, a large solar thermal plant in Graz (Austria), depicted in Fig. 2, was equipped with high-precision measurement equipment (i.e. high-precision irradiance, temperature and volume sensors as specified below). In this plant, six collector arrays with high-efficiency flat plate collectors of five different producers are measured (total gross collector area: 2,150 m^2). Fig. 3 shows the positions of the volume flow and temperature measurements. Each array has a separate volume flow sensor (electromagnetic flow sensor *KROHNE OPTIFLUX 4000*). The inlet and outlet temperature of each array and the flow temperatures for each row are measured. For one specific row, additional measurements of the inlet and outlet temperatures of single collectors are put in place. All temperatures are measured directly in the fluid with PT100 sensors of tolerance class DIN EN 60751, F 0.1. Total irradiance in the collector plane is captured by a pyranometer (*Kipp & Zonen SMP 21*). For the measurement of beam irradiance, a pyrheliometer with an active solar tracking system device is used (*Kipp & Zonen SHP 1*). Wind speed and ambient temperatures are measured in three different spots. The sampling rate is one second. The aim of the measurement instrumentation is to achieve precisions comparable to outdoor measurements of accredited collector test laboratories. The setup allows a direct side-by-side comparison of the different collector types. Data are available since August 2016.

Fig. 2: High-precision measurement of a large solar thermal plant in Graz (Austria)

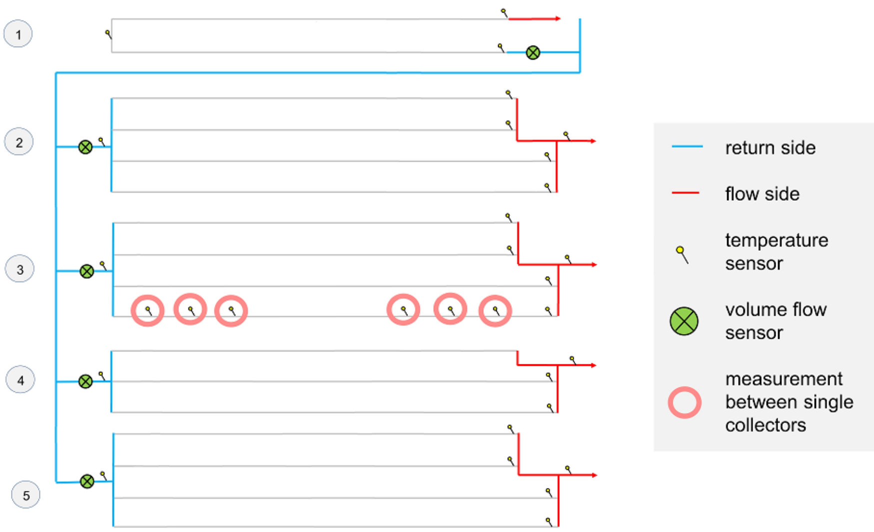

Fig. 3: Measurement setup of the volume flow and temperature sensors

4. Major challenges of in-situ collector array testing

General requirements of technical test procedures are the validity, reliability and accuracy of the procedure. The main challenges to achieve this are listed below.

4.1 Correct determination of the beam and diffuse irradiance on the collector plane

Problem description

The beam and diffuse irradiance on the collector plane are the most important influencing factors of the thermal power output of the collector array. Three main issues are relevant here:

- **Internal shading** due to collectors placed in front
- **External shading** due to surrounding objects (buildings, trees, etc.)
- **Unequal distribution of beam and diffuse irradiance and non-representative sensor readings.** Typically, not all parts the collector array receive the same amount of beam and diffuse irradiance. The front row is not exposed to internal shading and external shading depends on the position in the array relative to the sun and the surrounding objects. Different sky view factors between the collectors and along the collector height of single collectors, different albedo values of the ground, etc. lead to a varying diffuse irradiance. This makes a representative measurement of the irradiance on a single 'reference position' difficult. The irradiance recorded by the radiation sensors and the irradiance the collectors are exposed to might diverge to a point where the sensors are shaded and the rest of the field is not or vice versa.

These issues have been analyzed using data of the SDH test plant described in chapter 3. Fig. 4 shows two images of the 3D model of the plant, taken in the morning and afternoon for a sample day. At 8.43h (left), external shading can be spotted, at 16.30h (right) internal shading can be seen. Furthermore, the pyranometer positioned in the middle of the array, is shaded by an external object, whereas most collectors are not.

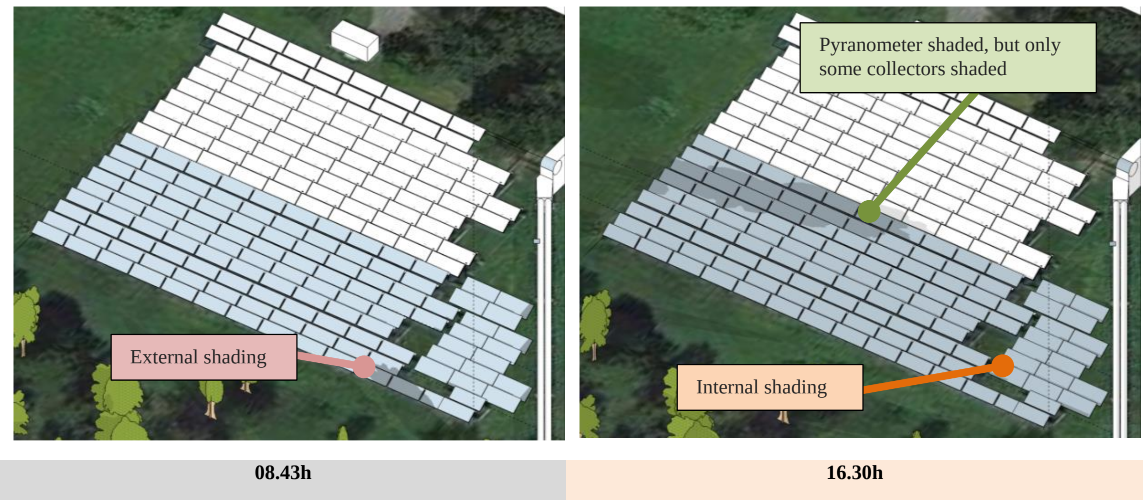

Fig. 4: Irradiance analysis of the test plant (2017-09-27)

Implications for in-situ collector array testing

When internal and external shading is not accounted for and the sensor readings differ from the irradiance the collectors are exposed to, the assessment of the collector array performance is not adequate because the energy input to the system is not calculated correctly. Usually the irradiance is overestimated, as the pyranometer which measures the total tilted irradiance is placed above the collectors where it is less exposed to shading and has a larger sky view factor than the lower parts of the collector. If a collector has an optical efficiency of $\eta_0 = 0.8$ and the irradiance on the collector at normal incidence is overestimated by 10% (e.g. 880 W/m^2 instead of 800 W/m^2), then the calculated optical efficiency is mistakenly assumed to be $\eta_0 = 0.73$, which makes a huge difference.

4.2 Collector array dynamics

Problem description

Large collector arrays show a highly dynamic behavior due to abrupt changes of the irradiance, return temperature and volume flow (variable speed pumps are the standard in large scale applications). For in-situ testing, there is only a limited possibility to impose stationary conditions due to technical and economic constraints. The dynamic behavior places an import role in the overall collector array assessment.

For large collector arrays, the dwelling time of the fluid in the collector array (i.e. the time that elapses between the entrance of a fluid element volume in the collector array and its exit) is determined by the volume flow rate. It is often in the range of 2 to 3 minutes and can reach up to 10 minutes. The dwelling time influences the dynamic behavior to a large extend, the time constant and the heat capacity will vary accordingly.

In Fig. 5, the issues regarding the dynamics are exemplified by analyzing the response of the outlet temperature when swift changes of the irradiance, return temperature and volume flow rate occur. Depicted are five arrays of the test plant. After the volume flow rate decreases (1), the outlet temperature rises steadily over the course of ten minutes (2) and starts decreasing again after the volume flow rate is put back to the initial level (3). A swift increase of the return temperature (4) leads to lower outlet temperatures. The two effects interfere (5).

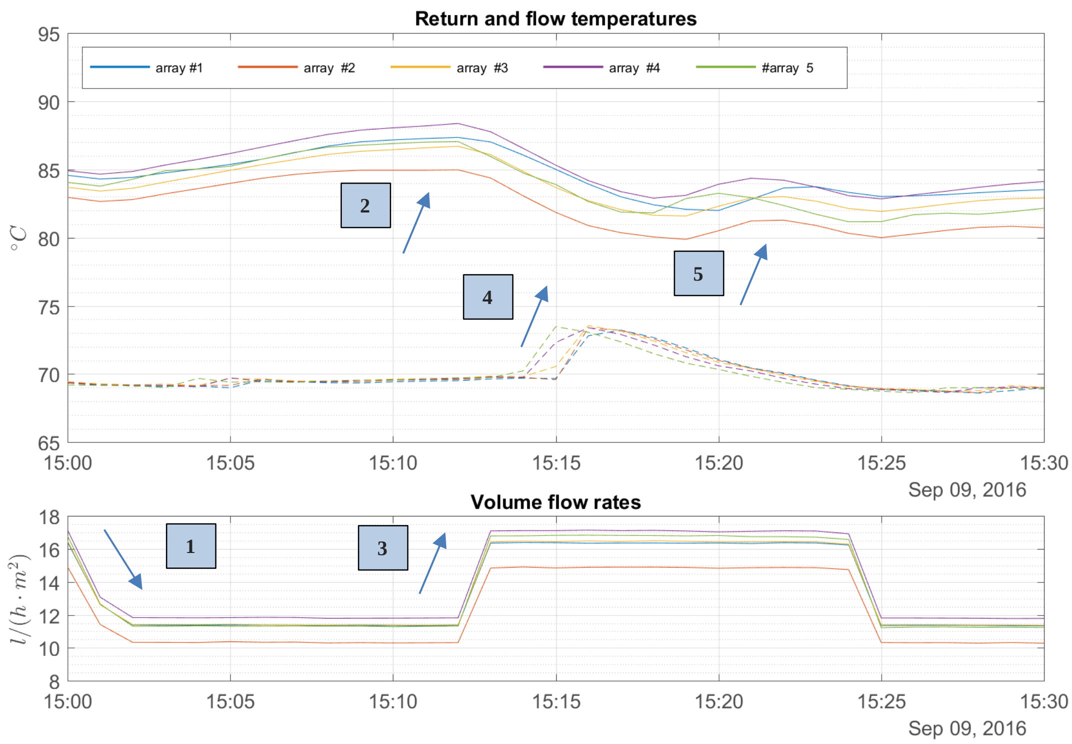

Fig. 5: Delayed response of the collector array outlet temperature (2, 5), when swift changes of the volume flow rate (1, 3) and return temperature (4) occur. Depicted are five arrays of the test plant.

Implications for in-situ collector array testing

If the modeling of the collector array outlet temperature does not take the delay that the dwelling time causes into account, then changes of the irradiance, return temperature and volume flow rate are mistakenly assumed to have an immediate effect. This leads to an inaccurate prediction of the short-term thermal power output and wrong estimates for the time constant and heat capacity values.

4.3 Availability of measurement data

Problem description

The challenges regarding the available measurement data are the following:

- **Limited operating range**. Most large scale installations feed into a district heating network. The most common connection is Return/Supply (R/S), which implies that the return and flow temperatures of the solar loop will usually be close to the (stable) grid return and flow temperatures. Data with a low temperature rise between the return and flow side (these conditions are needed to determine the zero loss coefficient) are usually not available.
- **High correlation of total tilted irradiance and the mean collector array minus ambient temperature**, as low irradiance levels lead to lower outlet temperatures and higher irradiance levels lead to higher outlet temperatures.
- **Sensor readings are not representative**. This problem is most prominent for the irradiance measurement as was pointed out before. But the issue also applies to the wind speed or ambient temperature measurements. The wind speed in the collector plane varies a lot across the array and cannot be measured adequately for collector arrays (for single collector testing, ISO 9806 requires to measure the wind speed on four edges of the collector).
- **Accuracy and precision of commercial measurement equipment.** Commercial installations often use low-cost sensors (especially for the irradiance measurements) and sensors might not be installed correctly (e.g. temperature sensors with too low penetration depth).
- **Missing measurement points.** Some inputs might not be directly measured, it can be needed to calculate them (e.g. the primary volume flow, derived from the return temperature, flow temperature and fluid properties of the primary side and the thermal power measurement of the secondary side). This can lead to additional uncertainties.

In Fig. 6, a bi-variate histogram of the total irradiance on the collector plane and the collector array mean minus ambient temperature of one-year data of one subfield of the test plant is shown. This distribution is typical for SDH plants. Most of the data lies in a close range and the irradiance and temperature are positively correlated.

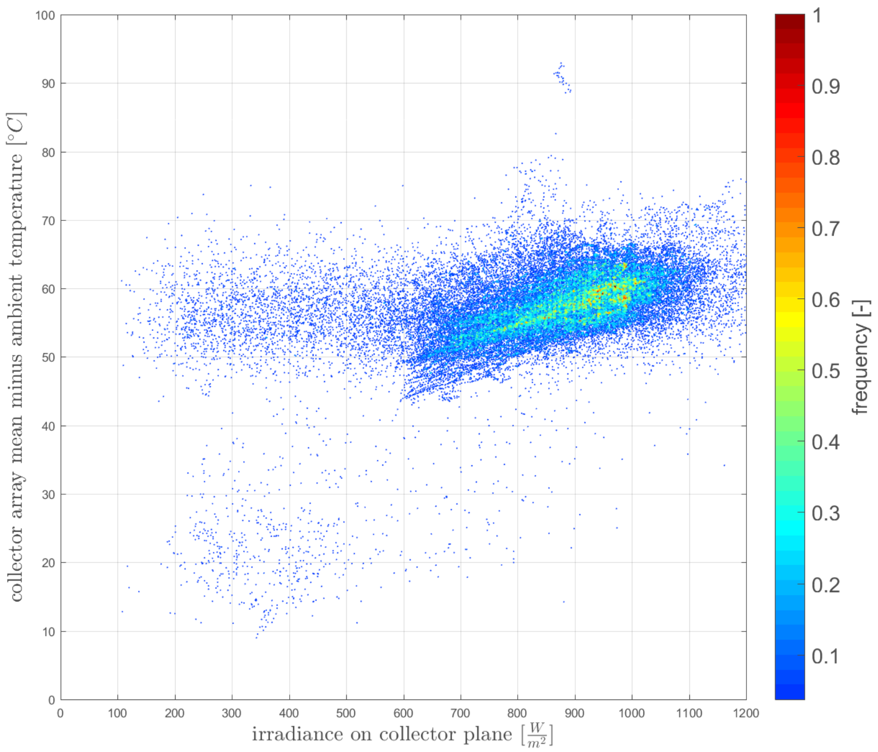

Fig. 6: Bi-variate histogram of the total irradiance on the collector plane and the collector array mean minus ambient temperature

Implications for in-situ collector array testing

A limited operating range and a high correlation of the irradiance and the collector array temperatures can lead to unstable parameters and overfitting. Optical parameters (zero loss efficiency, incidence angle modifier) and heat loss coefficients cannot be distinguished properly. Sensor readings that are not representative and low measurement data quality can lead to a bias.

4.4 Conflict of interest regarding the goals of the procedure

Problem description

For in-situ collector array testing, the following trade-offs need to be addressed:

- **Precision vs. easy applicability**. A detailed modeling of the collector array and strong restrictions regarding measurement data (sensor precisions, data range, data variation, etc.) lead to a more precise characterization of the collector array, but hinder an easy applicability. For example, a detailed modeling of the temperature and flow distribution increases the exactness, but requires a big effort and detailed analysis.
- **Comparability vs. broad applicability**. Different flat plate collector types, collector tilts and orientations, hydraulic layouts, flow conditions in the absorber pipes, varying levels of soiling, etc. might compromise the comparability. At the same time, the test procedure needs to be flexible regarding different plant configurations.
- **Choice of system boundaries**. The choice of system boundaries depends foremost on the available measurement points, but also encompasses choices regarding the attribution of losses. For example, if the heat exchanger losses are not attributed to the collector array, systems with no heat exchanger and active anti-freezing protection might have a disadvantage.

Implications for in-situ collector array testing

The advantages and disadvantages need to be balanced. The general approach of the developed in-situ collector array test is to lean towards easy and broad applicability rather than exactness.

5. Framework for in-situ collector array testing

A framework to address these challenges is covered in this chapter. The major building blocks are:

- **Collector rows as basic modeling blocks**. The core entity when modeling the primary side of large collector arrays is one collector row. A collector row has a well-defined volume flow and inlet and outlet temperature. These variables can be measured at the system boundaries or inferred if they are not given directly. The temperature rise between the cold and hot side of a collector row is usually sufficiently large, such that the thermal power output can be determined with reasonable accuracy. A collector row has also a well-defined (mean) dwelling time. Furthermore, a collector row can in most cases be treated as homogenous regarding tilt, azimuth and irradiance (the internal shading of the collectors is usually similar for all collectors of one row). Irradiance measurements in the collector plane in one spot of the row have in most cases the same (potential) bias for all collectors. A collector row behaves similar to a large collector and can (for the most part) be described with collector parameters. However, changes in the flow regime (laminar/turbulent) need to be carefully evaluated.
- **Finite volume collector array model**. A reasonable simplification to model a single collector row is a finite volume model which treats the collector row as a pipe with one-dimensional heat transfer in the flow direction. The predicted variable of the model is the collector row outlet temperature. By applying an energy input/output balance to a fluid element volume one obtains a hyperbolic differential equation for the fluid temperature. The fluid temperature $T_f(z,t)$ at position z and time t can be modeled as follows

$$\frac{\partial T_f(z,t)}{\partial t} = -\frac{V(t)}{A_f} \cdot \frac{V_{col}}{A_{col}} \cdot \rho_f \cdot c_f \cdot \frac{1}{(mc)_{sp}} \cdot \frac{\partial T_f(z,t)}{\partial z} + \frac{1}{(mc)_{sp}} \cdot \alpha(R(t)) \; - \frac{1}{(mc)_{sp}} \cdot \gamma(T_f(z,t) - T_a(t))$$

  where $V(t)$ is the volume flow, A_f is the pipe cross section area, V_{col} is the total fluid content of the row, A_{col} is the total collector area, $(mc)_{sp}$ is the specific heat capacity, $\alpha(t)$ is an absorption function for the beam and diffuse irradiance *R(t)*, γ is a heat loss function (usually a second order polynomial) and $T_a(t)$ is the ambient temperature. This modeling approach is widely used (see e.g. Lemos, Neves-Silva, and Igreja (2014))

If there is no significant maldistribution of the volume flow across the array, then the effect on the thermal performance will be marginal, and a whole collector array can be modeled as a single row (and a single row as a pipe). Modeling the collector array as a single pipe or multiple pipes with one-dimensional heat transfer in the flow direction is a reasonable balance between precision and easy applicability as well as comparability and broad applicability.

- **Irradiance modeling**. For a correct determination of the beam and diffuse irradiance on the collector plane an irradiance model of the plant is necessary, which is able to calculate the irradiance distribution on the collector array (beam and diffuse) based on the sensor readings (total tilted irradiance and beam DNI irradiance). Many tools and algorithms were developed, they date back to the 1970s (see e.g. Appelbaum and Bany (1979)). However, they need to be adapted to large collector arrays. The simplest approach is to check if there is any internal or external shading and exclude these conditions from the parameter estimation procedure.
- **Design of experiments**. Whenever possible, data of the normal plant operation should suffice for in-situ testing. If the operating range or the variation in the data are so little, that the test procedure cannot be applied, a carefully designed test to obtain more data can be conducted. For most plants, the return temperature can be lifted (diminishing the load or mixing return and flow side). This variation has to be done for different irradiance levels to gain uncorrelated measurements of the irradiance and collector array temperatures. Additionally, periods with low temperatures at the heating up or cooling down operation phase of the plant can be used.
- **Reducing modeling complexity**. To reduce the modeling complexity, basic checks can be performed to make sure that minor influencing factor on the thermal performance remain within acceptable ranges. For example, instead of modeling the volume flow distribution, one can check if the flow distribution is roughly balanced by evaluating the outlet temperatures of the collector rows.
- **Statistical data evaluation, modeling of uncertainty**. To deal with commercial measurement equipment and missing measurement points, the explanatory variables and the dependent variable need to be modeled stochastically and the measurement and modeling uncertainties need to be taken into account.

6. Conclusion and Outlook

The major challenges for in-situ testing of large collector arrays were identified and a framework to address them was developed. The next step is to elaborate the in-situ test procedure based on this framework, implement it in a software environment, apply it to the test plant and validate it.

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