IEA SHC Task 49

Solar Process Heat for Production and Advanced Applications

SolarPACES Annex IV

Guideline on testing procedures for collectors used in solar process heat

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IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

The members of the IEA SHC collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 57 such projects have been initiated, 47 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

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- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
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1 Preliminary remarks

Solar process heat collectors include a wide range of collector technologies, from standard flat plate collectors over air heating collectors to highly concentrating Parabolic Trough or Linear Fresnel collectors. All of these technologies compete against conventional energy sources but may also compete against other renewable energies and even against each other.

To enable solar thermal technologies to successfully enter the important market of process heat applications, it is crucial for the manufacturers to be able to provide reliable figures to succeed in tenders, to be able to predict energy yields with sufficient accuracy and to be able to prove liability in operation. All of this requires commonly agreed key figures and testing procedures to provide these.

Existing test standards provide solutions for many of these questions and the majority of technologies. First and foremost the ISO 9806:2013, which origins in the field of low temperature domestic hot water systems, has a wide scope and nowadays also includes highly concentrating collectors. But as the range of solar thermal technologies has much increased, and the formerly almost separated fields of non-concentrating low temperature and concentrating high temperature applications meet and merge in the middle, many questions arise, as to how all of these can be tested and compared fairly.

The present guideline targets manufacturers, project engineers, contractors and end-users and tries to give an outline of the existing regulations to be aware of, to help understand, interpret and compare test results and to also highlight lacks and shortcomings in the directives that may be obstructive to fair competition. It is clearly not intended to treat every technical question in detail, but rather to name the issues and hinting towards possible solutions, relevant publications and further work to be done.

In spite of the diverse technologies available, the present guideline mostly focusses on problems connected to concentrating collectors as no contributions from other fields were made.

2 CE marking

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The following chapter presents in detail the regulatory environment from the European point of view. As national regulations often go beyond these requirements, please refer to the country's regulatory specificities in which a project is developed.

2.1 General aspects

When the CE mark is applied to the machine, this signifies that the manufacturer has carried out all the tests, examinations and evaluations to prove that the product meets all the essential safety and health requirements of all directives or regulations concerned by this product.

The CE marking is affixed by the **manufacturer** after completion of due process.

In order to obtain a certificate of compliance, the manufacturer needs to draft technical sheets and sign a CE Declaration of Conformity.

In the case of projects composed of different sub parts, the Engineering, Procurement and Construction (EPC) Company connecting all parts together is in charge of CE Marking, including the different parts "declaration of incorporation". Every part supplier is in charge of all the "partly completed machinery" documentation.

The documentation must always be available to the authorities on request. If the product is manufactured in a third country, it is the importer who must verify that the manufacturer has complied with all prescribed procedures and provides the necessary documentation. The documentation needs to be available in the language of the country where the project is built.

A third party inspection body can also participate in attestation of conformity procedures following the legislation specifications. Depending on the CE system category a product type is defined in, information for CE marking might partly have to be provided by a so called notified body (a third party with a specific accreditation).
Depending on the kind of solar process heat installation, one or several directives need to be considered.

2.2 Directives applying to all solar process heat installations

The following directives can a priori be applied to products in solar process heat installations.

2.2.1 Pressure Equipment Directive (PED)

Every hydraulic loop matching the given conditions needs to follow this Directive.

Directive 97/23/EC on Pressure Equipment specifies the essential requirements the product must meet in order for the manufacturer to affix the CE Marking.
The Directive defines pressure equipment as vessels, piping, safety accessories and pressure accessories and applies to the design, manufacture and conformity assessment of pressure equipment and assemblies with a maximum allowable pressure PS greater than 0.5 bar.
The pressure equipment covered by the Directive is subject to the essential safety requirements listed in Annex I of the Directive. The requirements focus on hazard reduction, apply appropriate protection from hazard where it is not avoidable and inform on any hazard that cannot be eliminated (European Parliament and European Council 1997).

2.2.2 Machinery Directive

This directive can be applied to installations using trackers to follow the sun.

Machinery means: an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves and which are joined together for a specific application.

Directive 2006/42/EC on Machinery specifies the essential health and safety requirements the product has to meet in order for the manufacturer to affix the CE marking.

Directive 2006/42/EC covers machinery; interchangeable equipment; safety components; lifting accessories; chains etc. It also includes requirements for partly completed machinery.
The first step a manufacturer should take to ensure that a machine will be compliant with the Directive is to carry out an assessment procedure with regard to the essential requirements. This includes also checking which European Harmonized Standards are applicable, as a way to get presumption of conformity. Annex I to Directive 2006/42/EC sets out in detail the essential health and safety requirements for the products covered (European Parliament and European Council 2006a).

2.2.3 Low Voltage Directive

Any electrically driven equipment has to comply with this directive. This directive is included into the Machinery Directive and therefore do not need to be considered when this one is already taken into account.

Directive 2006/95/EC on Low Voltage Devices specifies in detail the essential requirements the product must meet in order for the manufacturer to affix the CE marking.
It is intended to remove all obstacles to the sale of low voltage electrical equipment within the EU, while at the same time ensuring that they offer the highest possible level of safety.

'Low voltage devices' are defined as any equipment designed for use with a voltage rating between 50 and 1,000 V for alternating current and between 75 and 1,500 V for direct current.
The Directive 2006/95/EC specifies that equipment must not endanger the safety of people, animals or property 'when properly installed and maintained and used in applications for which it was made'. The key safety objectives for equipment covered are listed in Annex I (European Parliament and European Council 2006b).

2.3 Directives for special cases

The two directives below may be considered in some specific cases.

2.3.1 Electromagnetic Compatibility Directive (EMC)

This directive is included into the Machinery Directive and therefore does not need to be considered when that is already taken into account.

Directive 2004/108/EC on Electromagnetic Compatibility (EMC) specifies in detail the essential requirements the product has to meet in order for the manufacturer to affix the CE marking.
It is intended to ensure that equipment liable to generate or to be affected by electromagnetic disturbance can be used in the electromagnetic environment for which it has been designed without causing disturbances to other equipment or being affected by them. The 2004 Directive updated and replaced Directive 89/336/EEC, which had previously regulated this area.

The essential requirements regarding electromagnetic compatibility for equipment are set out in Annex I of the Directive.

The EMC Directive covers apparatus sold as single functional units to end users, which are either liable to generate electromagnetic disturbance, or could see their performance affected by it. It does not cover equipment which is specifically intended to be incorporated into a fixed installation and is not otherwise commercially available (European Parliament and European Council 2004).

The EMC Directive does not apply to radio equipment and telecommunications terminal equipment, as this is covered by Directive 1999/5/EC. Aeronautical products and radio equipment used by radio amateurs are also excluded from the scope of the Directive.

2.3.2 ATEX (Equipment and protective systems intended for use in potentially explosive atmospheres) Directive

The ATEX Directive 94/9/EC on equipment and protective systems intended for use in potentially explosive atmospheres specifies in detail the essential requirements the product has to meet in order for the manufacturer to affix the CE marking.
In addition to equipment and protective systems, the directive also applies to safety devices, controlling devices and regulating devices for use outside potentially explosive atmospheres but needed for the safe functioning of ATEX equipment and protective systems. For further details on the products covered please consult Chapter I, Article 1 of the ATEX Directive 94/9/EC.

The essential health and safety requirements – as set out in Annex II of the Directive – foresee among others that products must be designed with a view to integrated explosion safety. They can only be manufactured after due analysis of possible operating faults in order to preclude dangerous situations as far as possible. In this sense, the products must be accompanied by instructions and must be marked legibly and indelibly with a list of minimum particulars such as the name and address of the manufacturer, designation of series or type, the specific marking of explosion protection followed by the symbol of the equipment group and category and others. Furthermore, where necessary, they must also be marked with all information essential to their safe use.
In terms of selection of materials, the Directive requires a special selection of risk-reducing materials as laid down in Annex II, 1.1 (European Parliament and European Council 1994).

2.4 Construction Products Regulation

The Construction Products Regulation (European Parliament and European Council 2011) was published in 2011. As it is a regulation, it is legally binding in all EU member countries (in contrary to a Directive, which is to be transferred into national law within three years). In almost all cases, a solar collector is interfering with the energetic behavior of a building, which is why the EU-CPR is applied on solar collectors (Article 2, Clause 1). Collectors are defined to be handled within System 3 of CE marking. This indicates that the manufacturer has to document a factory production control (FPC) and an initial test for the product type. The initial product type test has to be performed by a notified testing laboratory. Basis of the testing is in this case the harmonized standard hEN 12975. This standard is not published yet but under development (expected DoA summer 2016). Until then, compliance with the requirements of EU-CPR can be approved by a European Technical Assessment (ETA) procedure. Identifying the same criteria of performance but transferring the responsibility of “how those criteria are tested?” from a (harmonized) standard to a notified body which puts together the relevant testing schedule.
The so called performance criteria to be declared by the person marketing the product are listed in Table 1.

Essential characteristics	Performance[1]	Harmonized technical specification
Mechanical resistance to climatic loads (wind, snow …), expressed as... - Positive loads - Negative loads	5400 Pa 2400 Pa	hEN 12975-1:201x
Fire safety, in terms of... - Reaction to fire - External fire performance	A1 B roof (t2)	
- Weather tightness	No water ingress	
- Release of dangerous substances	None	
- Electrical safety	Safety class II	
- Maximum operating pressure	1 MPa	
- Sound level		
- Thermal output	2700 W	

Table 1: Table ZA.1.1 — relevant clauses for fluid heating solar collectors intended for use in buildings (prEN 12975-1 2011)

[1] The values given are just indicative examples.

3 Functional testing and self-protection

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Apart from collector efficiency the quality, durability and intrinsic safety of a collector is of high importance. Before the publication of EN ISO 9806:2013 no relevant testing standard featured solutions or guidance for the specific challenges of collectors which work in elevated temperature and pressure ranges and, thus, are predestined for the use in process heat applications, e.g. concentrating collectors (Kramer et al. 2011). First steps towards the solution of these issues were taken within the European QAIST project (Kovacs P. et al. 2012) for the revision of the former EN 12975 (EN 12975-1 2006; EN 12975-2 2006), which was an intermediate step in the development process of the current testing standard (Mateu Serrats et al. 2012).
EN ISO 9806:2013 defines a set of functional and quality tests to be conducted on solar thermal collectors. Any collector tested according to the standard has to be built to resist the conditions, stresses and strains defined in the respective chapters or it has to provide safety means to avoid these limit cases. In that case, the executing test laboratory has to verify the satisfactory function of these safety features by defining a suitable test sequence. While the standard is very specific in setting the conditions and procedures for the testing conventional collectors without safety features it leaves a lot of room for interpretation in the appliance of these tests to collectors, which are not built to resist but to prevent hazardous situations, e.g. concentrating collectors (ISO 9806 2013).

The standard reads as follows in this matter:
"*Collectors shall be tested in such a way that they shall be able to demonstrate **suitable performance and ability to protect themselves** from common failures due to conditions that can arise in standard operation. The collector shall be assembled (if it is necessary) and its components shall **operate according to the manufacturer's specifications**. If the collector has active mechanisms which are intended to be functional during normal operation, those mechanisms shall be **operational during testing**. A tracking device, if it is present, shall be supplied by the collector manufacturer and shall be used during the tests. […] The protection systems can be active, such as actuators, motors and other equipment, or passive, such as materials reacting to heat or other designs. **The manufacturer shall clearly define the equipment protection features** and shall specify whether or not the equipment **requires an external energy source** to operate.*
*The collector can present a combination of active and passive controls, and in that case the test sequence shall be selected to **verify suitable operation** of active and passive mechanisms **during normal operating conditions. (ISO 9806 2013)*** "

This chapter summarizes the core requirements of the standard and the discussion of the working group on function tests and self-protection mechanisms within the subtask A of IEA Task 49, as well as the interpretations derived from it. It gives recommendations on how to perform each functional test necessary and how to perform tests on substitutional safety features. It also highlights remaining issues for the application of these tests on concentrating collectors.

3.1 Internal pressure test

This test is intended to assess whether the piping of the collector can withstand the pressures it will meet in regular operation. The collector is to be tested with 1.5 times the nominal maximum operating pressure using an apparatus consisting of a hydraulic pressure source, a safety valve, an air-bleed valve and a pressure gauge with a standard uncertainty better than 5%. The standard defines different ambient test conditions for organic and inorganic absorbers.
Test pressure shall be maintained (± 5%) for 15 min. Fluid channels are inspected for swelling,

distortion or ruptures (ISO 9806 2013).

Special specifications or alternatives for self-protecting collectors are not included.

Recommendation for self-protecting / concentrating collectors:
The test is to be performed according to the standard **unless** proof of an equal or superior test procedure performed by an accredited institution can be supplied by the manufacturer. In case of concentrating collectors this is often covered by the requirements of the PED and already done before a collector goes into testing.

3.2 High temperature resistance test

This test is intended to assess whether all components of a collector can withstand the maximum temperatures it can reach during normal operations by exposing it to high irradiance and ambient temperature for one hour. For collectors without safety features and designed to withstand stagnation, the high temperature test is to be performed without heat transfer fluid (HTF).
*"In case of collectors using external power sources and active or passive measures for normal operation and self-protection, **high-temperature resistance test shall be carried out** during the exposure test. **If controls are present to manage both a no-flow and high-temperature condition**, the collector shall be **filled with heat transfer fluid** […]. The collector shall operate close to the **maximum operating temperature** defined by the manufacturer […]. In that case the controls shall be checked [...] (ISO 9806 2013)."*

Recommendation for self-protecting / concentrating collectors:
Due to obvious reasons highly concentrating collectors cannot withstand dry stagnation and, thus, are bound to feature **no-flow and overheating protection, as well as an uninterruptable power supply in case of active safety measures, as minimum safety equipment** to pass the quality tests of ISO 9806:2013. The safety features shall be checked by deliberately exceeding the set values and interrupting grid connection.

3.3 Standard stagnation temperature

The intention of this test is to assess the maximum temperature a collector can reach under standardized ambient conditions and to verify that the standard stagnation temperature, given by the manufacturer on the collector label and in the manual, is not exceeded. The standard provides two applicable methods to determine the standard stagnation temperature (ISO 9806 2013):

- Measurement of absorber temperature in dry stagnation and extrapolation to standard conditions
- Determination from efficiency parameters

Recommendation for self-protecting / concentrating collectors:
For self-protecting / concentrating collectors the determination of the standard stagnation temperature seems irrelevant as they are not intended to be operating under stagnation. Instead the manufacturer has to establish a maximum operating temperature allowed. Within the exposure test the resistivity of the collector to the maximum operating temperature can be verified.

3.4 Exposure and pre-exposure test

Objective of this test is a low cost liability and durability assessment and a preconditioning of the

collector for the subsequent quality tests, to ensure more realistic and repeatable results. The collectors are to be exposed to natural weather conditions until the specifications in Table 2 are fulfilled. Again, collectors designed to withstand dry stagnation are to be exposed without HTF while otherwise applies:
"[…] collectors shall be filled with the heat transfer fluid and such controls shall be verified. […]The manufacturer shall identify all active and passive controls which are present in the collector for protection purposes, such as controls, motors, actuators or other elements. The manufacturer shall submit to the laboratories their control set points and parameters in order to verify their suitable operation during normal working conditions in which events as over temperature, wind, etc. can affect the collector lifetime and its performance. The laboratory shall establish a test cycle in which all active and/or passive controls (if they are present) which are necessary to keep the collector in working order can be verified during the exposure period. Their operation shall be validated to be functional, in such a way that any failure can be detected. The test cycle shall include as events, the loss of electrical supply and the blockage of tracking mechanism (if it is present). The laboratory shall check the collector response and its ability to overcome (or not) such events (ISO 9806 2013)."

Climate conditions	Values		
	Class C	Class B	Class A
Global solar irradiance on collector plane during minimum 30 hours (15 hours in case of pre-exposure) G [W/m²], T_amb [°C]	800/10	900/15	1000/20
Global irradiation on collector plane for exposure test during minimum 30 days [MJ/m²]	420	540	600
Global irradiation on collector plane for pre-exposure test during minimum 30 days [MJ/m²]	210	270	300

Table 2: Requirements and classes for the exposure test, chosen by the manufacturer (ISO 9806 2013)

Recommendation for self-protecting / concentrating collectors:
It can be concluded, that if the exposure is conducted with HTF, test can be combined with efficiency testing sequences.
Problematic for concentrating collectors can be the classification according to Table 2 as it was compiled for global irradiance measurement in the collector aperture plane, tilted according to the latitude of its location. As some types of collectors cannot be tilted as a whole, they may hardly be able to reach the values of Table 2 depending on their latitude. This raises the question how to measure irradiance and / or do the classification for such types of collectors. The following possibilities occur:

- Compiling an additional table based on direct normal irradiance (DNI) or global horizontal irradiance measurement
- Installation of an pyranometer **not** in the aperture plane but tilted according to the latitude and classify the collector according to Table 2

This question should be addressed in TC 312 WG1. As the same problem arises for the thermal shock tests, the recommendation applies likewise.

3.5 External thermal shock

Objective of this test is to assess whether collectors are able to withstand thermal shocks caused by sudden rainstorms while being on the maximum temperature to be reached in regular operation. Collectors are to be tested without HTF and have to be exposed for one hour to the conditions in Table 2 before the test (ISO 9806 2013).

For the external thermal shock test the standard lacks specific instructions for self-protecting collectors, which raises the following questions:

- Collectors, to which dry stagnation is not bearable, are inexplicitly forced to provide no-flow and overheating protection to be able to pass testing according to ISO 9806:2013. Accordingly, it can be assumed that the external thermal shock has to be conducted providing HTF-flow in the collector, but the standard does not state at which operating temperature the test shall be performed. The obvious solution would be to adopt the regulations of the other functional test and to perform it at maximum operating temperature.
- Is the test at all relevant for concentrating collectors using evacuated tubes which in case of Linear Fresnel Collectors (LFC) are additionally covered with a secondary reflector?
- How can an adequate water spray be provided on the receiver often located high above ground?
- Can the test be substituted by component based function tests, for e.g. by a water droplet test on the receiver tubes

These questions should be addressed in CEN TC 312 WG 1 and / or ISO TC180.

Recommendation for self-protecting / concentrating collectors:
The external thermal shock tests should be performed at maximum operating temperature, if feasible. Otherwise the test laboratory shall establish a test cycle for component wise testing of parts it considers to be sensitive to external shock.
Concerning the ambient conditions, the recommendation of chapter 3.4 applies.

3.6 Internal thermal shock

Objective of this test is to assess whether collectors are able to withstand thermal shocks caused by sudden intake of cold HTF while being on the maximum temperature to be reached in regular operation. Again, collectors without safety features to prevent stagnation are to be tested without HTF and have to be exposed for one hour to the conditions in Table 2 before the test, while collectors with no-flow protection are not subject to this test at all (ISO 9806 2013).

3.7 Rain penetration test

The test is only applicable to glazed collectors and shall assess the extent to which collectors are able to handle rain penetration. Collectors subject to this test shall be sprayed with water for 4 hours with the apparatus and under the conditions described in the standard and the extent of water ingression is to be assessed (ISO 9806 2013).
The standard lacks specific instructions on how this is to be applied to concentrating collectors, for which an artificial irrigations in compliance with the regulations does not seem feasible and in most cases neither necessary nor constructive.
The following questions have to be addressed in CEN TC 312:

- Which parts of concentrating collectors are at all vulnerable to rain penetration (switch-boards, drives and suspension, receiver, secondary reflector, safety devices)?

- Can the verifiable use of parts with sufficient IP classification or other measures substitute the test?
- How can the test procedure in the standard be adapted for these technologies or substituted by another (e.g. minimum amount of rainfall within exposition test and evaluation at final inspection)?

Recommendation for self-protecting / concentrating collectors:
Testing of an entire concentrating collector such as LFC of Parabolic Trough Collectors (PTC) appears to be neither feasible nor reasonable as most parts of the structure are not vulnerable to rain penetration. The test laboratory shall establish a component based test cycle for all parts sensitive to rain penetration. Verifiable IP classification submitted by the manufacturer shall be accepted as equivalent and listed in test report.

3.8 Mechanical resistance test

Objective of the test is to assess a collector's resistivity to positive and negative mechanical loads caused by winds and snow, including its fixings. The standard provides different equivalent testing procedures while the stress limitations are to be defined by the manufacturer.

As the above mentioned procedures will in most cases not be applicable to concentrating collectors due to their dimensions, the standard allows that the laboratory may design specific and suitable procedures to test the resistance of concentrating collectors against mechanical load.

In case controls against wind or snow load are present, the control functions shall be checked and they shall demonstrate resistance to failures associated with normal collector operation (ISO 9806 2013).

Recommendation for self-protecting / concentrating collectors:
Because the load limits are to be defined by the manufacturer and can be set to zero, the test can even be avoided with due reference in the test report. In this case, component wise mechanical load testing is possible and advised for parts sensitive to it, e.g. reflectors with their substructures. This does of course not affect the distributor's liability to ensure the safety of the whole construction under the normal weather conditions to be found at the operating site which will usually be done by static calculations.

3.9 Impact resistance test

The test is meant to assess the collector's ability to resist the impact of hailstones and dipping tools. The standard indicates two possible test procedures, one using ice balls with defined diameter and mass and a shooting device with controllable speed. The other method is using steel balls with a specific mass dropped from defined heights. The impact resistance test is mandatory, but similar to the mechanical load test the limitations are to be defined by the manufacturer (ISO 9806 2013).

Recommendation for concentrating collectors:
Avoidance of the test is possible by defining ice ball diameter or dropping height as zero with due reference in the test report. Again, in this case the testing of vulnerable components such as primary and secondary reflectors or receiver tubes is advised.
It shall be noted, that some countries, e.g. Switzerland, provide regulations which exceed the requirements of ISO 9806 and may deny installation of collectors lacking proof of substantial impact resistance tests.

3.10 Summary

The guideline (Kovacs P. et al. 2012) that was written as a supplement to EN 12975 and to clarify its interpretation, will soon be revised to adapt it to ISO 9806:2013 in a project funded by the Solar Keymark Certification Fund (expected in 2016). In this process and in the future work of the responsible standardization bodies, the above mentioned questions concerning the application of specific tests to concentrating collectors have to be solved. Table 3 gives an overview on the necessary tests, their respective core requirements when executed, applicability to self-protecting collectors and possible substitutions, as well as additional hints and unsolved issues.

Test	Requirement[2]	Applicable to[2]	Substitution for standard procedure[2]	Additional hint[3]
Internal Pressure resistance	Max. operating temperature x 1.5	All collectors		Equivalent or superior proof of pressure resistance by qualified body e.g. within PED-qualification should be accepted
High temperature resistance	1h dry exposure at 1000 W/m² and 20-40°C	Collectors without high temperature and no-flow protection	Test with HTF flow at max. operating temperature, verify safety features	
Exposure and pre-exposure	Dry exposure according to Table 2	Collectors without high temperature and no-flow protection	Test with HTF flow, verify safety features	Can be combined with efficiency test, all safety functions must be operational
External thermal shock	1h dry exposure according to Table 2, water spray for 15 min at <25°C and 0.03-0.05 kg/sm²	All collectors		Open questions to be solved for concentrating collectors. For recommendations see chapter 3.5
Internal thermal shock	1h dry exposure according to Table 2, water perfusion for 5 min at <25°C and 0.02 kg/sm²	Collectors without high temperature and no-flow protection	Verify safety features	
Rain penetration	Heat collector to 55°C, water spray uniformly for 4h at <30°C, 300kPa and 2 kg/min per nozzle, spray angel 60°, apparatus as described in ISO 9806:2013	All collectors		Open questions to be solved for concentrating collectors. For recommendations see chapter 3.7
Mechanical resistance	Positive and negative load limits to be defined by manufacturer	All collectors, if procedure is feasible	Laboratory may design specific and suitable procedures	Can be avoided by setting limits to zero, load limits must be stated in the report
Impact resistance	Ice ball diameters / dropping height of steel ball to be defined by manufacturer	All collectors		Can be avoided by setting diameter / dropping height to zero, must be stated in the report

Table 3: Tests on function and self-protection mechanisms based on EN ISO 9806:2013 and additional hints from IEA Task 49 Subtask A.

[2] Extracted from ISO 9806
[3] Result from discussion in IEA Task 49 Subtask A

4 Component testing

4.1 Receiver

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The receiver is one of the most important components of solar thermal collectors.
The quality and long-term performance stability of the receiver has a crucial influence on how effectively solar radiation can be converted into heat. To achieve maximum efficiency, the receiver has to absorb as much solar radiation as possible and convert it into heat with minimized losses.
Main requirements for receivers for concentrating solar systems are the optical characteristics (absorptance of the absorber and transmittance of glass cover) and the heat loss of the overall receiver, including optically non-active parts. Further the durability for decades of outdoor weather exposure is required.
The international draft standard under preparation of the TC/SC 117 IEC NP 62862-3-3 gives a specification of the technical requirements, performance tests of the receiver, heat loss tests, and optical characterization tests as well as tests for durability and safety of technical performance parameters of solar thermal receivers. The heat loss test is based in the "Guidelines for the Laboratory Measurement of Parabolic Trough Receiver Heat Loss" drafted within the SolarPaces Task 3. This standard draft was proposed by the Spanish standardization Committee AEN/CTN 206/SC 117 "Thermoelectric solar energy systems" in AENOR and is based on the UNE standard draft under preparation for reflectors.
For heat loss and temperatures of receivers with a secondary reflector and non-evacuated absorber (Cavity- Receiver) the thermal interaction between mirror and receiver has to be taken into account (Heimsath et al. 2014b).

A summary of the standard draft submitted to the IEC committee is given in Sallaberry et al. (2015a):
"Receiver tubes aim to absorb the concentrated radiation at the focal line of parabolic trough and linear Fresnel collectors. The draft standard covers receivers with central absorber tube and glass envelope, specifying the relevant product parameters and tests. The main requirements are good overall absorption properties, low thermal loss to the ambient Q_{loss}*, and the durability for at least 25 years of daily operation cycles and outdoor weather exposure.*
The current standard draft includes definitions of technical properties, characterization of geometry and performance parameters as well as test methods. On the one hand, tests for heat loss and optical characterization of both the solar glass cover and solar absorbers tubes are considered. On the other hand, durability tests are described such as overheating and thermal cycling test procedures, stationary abrasion resistance test, impact resistance test, condensation test, selective absorber coating durability test, exposure durability test, stationary external and internal thermal shock test and thermal stability test, establishing some of them as mandatory tests to be approved and including others as recommendation as additional useful information of the component performance for the final user.
The heat loss test draft is based on the energy balance of an electrically heated receiver under stationary conditions (NREL 2009). Under these conditions, the heat loss is equivalent to the power needed to maintain the receiver at constant temperature. An experimental heat loss curve characteristic of the receiver tested is obtained as well as the calculation of thermal emittance from the power data measured at different temperatures. The results are quantified as power divided by nominal total receiver length, in W/m, dependence of the absorber tube to the temperature (Pernpeintner et al. 2015a; Pernpeintner et al. 2011). Several methods can be used for heating the receiver up to a given temperature. Key points of the test are the location and the contact of the temperature sensors inside the heated tube and accuracy of the power measurement in order to assure good measurements.

For optical characterization of receivers, destructive and non-destructive tests are described in the standard draft. The requirements for obtaining the solar absorptance of the absorber tube and solar transmittance of the glass envelope of the receiver respectively from spectrophotometric measurements are given. Particular care in using holders for curve samples and adequate working reference calibrated periodically should be taken. For non-destructive tests of optical efficiency (Pernpeintner et al. 2009; Mateu et al. 2012), all requirements about instrumentation and test conditions are specified, for example: spectral range, collimation, etc.

Some durability tests for the receiver are applied on the whole receiver tube whereas others are applied only in one element of the receiver. However, these tests imply the destruction of the component and do not give information about the performance of the whole component. That is why some other non-destructive tests, commonly used for comparison among different specimens, are also suggested in the draft.

Some durability tests were developed in the Spanish committee but not yet sent as proposals to the IEC committee:

Some of the tests are based on the methods proposed by Pernpeintner et al. (2015b). Most common tests on the entire receiver product include overheating tests (at proposed 80 K above max operating temperature, during 1000 hours) and thermal cycling tests (100 cycles with specified ramps), with comparative non-destructive measurement of heat loss and optical efficiency before and after the tests. Another example applied on the whole tube, is the test to determine the durability of the receiver tube bellows against mechanical fatigue. In the test in draft, the receiver shall be exposed to a minimum of 10,000 cycles of expansion and compression of the bellows and it is recommended to include two additional steps of 2,500 extra cycles. Heat loss tests shall be run before and after the test as evaluation checking. If the heat loss does not increase more than 30 % during the test and in the 24 hours waiting period after the cycling, the test is considered as passed."

4.2 Reflectors

Authors: A. Fernández-García (CIEMAT/PSA), L. Valenzuela (CIEMAT/PSA), F. Sallaberry (CENER) A. Heimsath (FHG-ISE)

Main requirements for mirrors for concentrating solar systems are the reflecting properties, the geometry parameters, in particular surface shape, and the durability for decades of outdoor weather exposure. The specifications are applicable to all types of concentrating solar technology variants.

The standard draft under preparation for reflectors in AENOR, the Spanish standardization Committee AEN/CTN 206/SC 117 "Thermoelectric solar energy systems"[4], includes the testing protocol established to characterize this component, both optically and geometrically, as well as the testing procedures to prove its durability both through accelerated aging tests and mechanical resistance tests. This standard is fully applicable to glass reflectors, although most of the testing procedures are applicable to solar reflector materials other than glass.

The measurement procedures applied in the standard to determine the reflectance and the shape (slope) of solar reflectors are refereeing on the guidelines developed and published under the framework of SolarPACES Task III (SolarPaces Guideline 2013b; SolarPaces Guideline 2013a). Hemispherical spectral reflectance is measured in 5 nm resolution with a spectrophotometer with integrating sphere (diameter at least of 150 mm) at 8° incident angle. For mirrors with high specularity, the hemispherical reflectance spectrum is weighted with the solar spectrum (direct normal) published in ASTM G173-03 (2012). The solar weighted hemispherical value is considered to be equal to the specular reflectance if the criterion of high specularity is fulfilled. Specularity is checked at specific wavelengths using a reflectometer with variable acceptance angles. Both measurements require traceable reflectance reference samples.

The increase of specular reflectance (Heimsath et al. 2015) within at least three defined acceptance

[4] http://www.aenor.es/aenor/normas/ctn/fichactn.asp?codigonorm=AEN/CTN%20206/SC%20117&pagina=1

angles between 7.5 mrad and 23 mrad should be tested for innovative reflectors.
For in-situ collector tests the soiling of reflectors has to be taken into account and measured thoroughly.

Reflector shape is characterized by slope measurements with photogrammetric and deflectometric techniques. High resolution is required to include the mirror rims. The resulting key parameter is the root-mean-square of the area-weighted local slope deviations from the design shape (flat, parabola, according to design) quantified in milliradians (parameter SD mrad). Trough mirror results are also converted in rms focus deviation (FD, in millimeter). More information about shape measurements is included in Section 5.

The goal of accelerated aging testing is to estimate the durability of the solar reflectors under several extreme weather conditions, while simulating them in a reasonable time of a few days or weeks. The following tests are proposed to determine the resistance of the functional coatings to the outdoor conditions in the solar field:

- Exposure to neutral salt spray test (NSS). The purpose of this test is to determine the resistance of the functional coatings to corrosion. It is based on the ISO 9227 standard (ISO 9227:2012). Samples are exposed to constant conditions of 35 ± 2 ºC with a spray of aqueous NaCl solution (50 ± 5 g/l, pH = 6.5-7.2) at 100% relative humidity (RH). The test shall last as minimum 480 h.
- Exposure to copper accelerated acetic acid salt spray (CASS). The purpose of this test is to determine the resistance of the functional coatings to corrosion. It is based on the ISO 9227 standard (ISO 9227:2012). Samples are exposed to constant conditions of 50 ± 2 ºC and 100% RH with a spray of aqueous solution of NaCl (50 ± 5 g/l) and $CuCl_2$ (0.26 ± 0.02 g/l), with pH-value adjusted to 3.1-3.3 using HCl, NaOH or $NaHCO_3$. The test shall last as minimum 120 h.
- Condensation test. The purpose of this test is to determine the resistance to corrosion under constant exposure to a condensation-water atmosphere. It is based on ISO 6270-2 standard (2005). Samples are exposed to a constant temperature of 40ºC and 100% RH. The test shall last as minimum 480 h.
- Cyclical exposure to temperature and humidity. Samples shall be subjected to a minimum of 10 cycles, each of which shall be comprised of the steps given in Table 4 and in the same order described. Step 3 may be substituted by 16 hours at 85ºC and 85% RH or 32 hours at 65ºC and 85% RH as requested by the manufacturer.
- UV radiation exposure test. The purpose of this test is to identify reflectors materials that are susceptible to be degraded by UV radiation. It is based on the ISO 11507 standard, and specifically on Type II or UVA 340 lamps (ISO 11507:2007). The test consists of the following cycle: samples are exposed during 4 hours at 60 ºC to UV-radiation and afterwards, the samples are exposed during 4 hours at 50 ºC to condensation (100% RH without irradiation). Samples of first-surface reflectors shall be exposed by the front side for at least 1000 h. Samples of second-surface reflectors shall be exposed facing the front side to the UV- lamps in the beginning for at least 1000 hours and shall be turned to the back side for at least 1000 hours, being the total testing time in this case at least 2000 hours.

Step	Duration (h)	Temperature (ºC)	Relative Humidity (%)
1	4	85	Not controlled
2	4	-40	Not controlled
3	16	40	98±2

Table 4: Conditions of steps in an exposure cycle

Inspection of samples after each test and evaluation shall include: (1) Type, number and size of damage appearing on the protective layers including delamination, peeling, bubbles, discontinuities, discoloration, etc., type, number and size of any damage to the reflective layer, including corrosion (on the edges or the surface) or discoloration. Density of degradation spots with diameter larger than 200µm shall be quantified. Failures on product edges (but not cut edge) shall be quantified. (2) Reflectance measurement before and after testing to determine the optical degradation of the material.
Concerning the mechanical durability resistance, the following tests are proposed:

- Mechanical tests (stressing to breaking point) - The purpose of this test is to determine the resistance of reflector fixation elements to pull-off forces similar to EN ISO 1015-12 (2000) or ISO 9806 (2013). It is applicable to reflectors commercialized with fixation elements. The test consists on applying growing force perpendicular to the surface of the attachment at a maximum speed of 1000 N/min. The test continues until the values specified by the manufacturer are reached or until detachment or breakage of the fixation or the reflector or its deformation.
- Abrasion resistance test. The purpose of this test is to measure the mechanical resistance of the reflector front surface to abrasion. This test is loosely based on the ISO 9211-4 (2012) standard. The specific parameters (rubber type and size, number of cycles, etc.) have to be defined.
- Impact resistance test (optional). The purpose of this test is to determine the extent to which the reflector can resist the effects of impact by hail. It is based on ISO 9806 (2013) standard. The test can be done by two different methods, with the use of ice balls or steel balls. The ice ball loses energy on impact, and is therefore more representative for the real effects of impact by hail. Therefore, it method is preferable for resistance testing.
- Safety performance under accidental impact test. The purpose of this test is to determine the safety performance of a reflector under accidental human impact. It is based on the ANSI Z97.1 (2009) standard.

4.3 Mirror shape accuracy

Authors: J. Fernández-Reche (CIEMAT/PSA), L. Valenzuela (CIEMAT/PSA), A. Heimsath (ISE)

Shape accuracy of optical components is a major factor for efficiently performance of concentrating collectors. For good collector performance, it is important, that as much solar radiation as possible hits the absorber or the receiver aperture as required.
The intercept factor of a solar collector is one of parameters that can be used to predict the thermal output of the system.
The intercept factor is defined as the ratio of the energy intercepted by the absorber to the energy reflected by the solar concentrator. Different techniques are available to measure the real shape of

solar collectors and determine the intercept factor.
Close-range *photogrammetry* is one of the techniques which are being used for shape quality assessments of solar concentrators. Initially the technique was applied for measuring new parabolic concentrators' prototypes at research centers, and during last years is being extensively applied in large scale solar collectors' fields (Shortis and Johnston 1996; Fernández-Reche and Valenzuela 2012; Lüpfert et al. 2007; Pottler et al. 2014).
Photogrammetry is a technique for quantitative analysis of measurements from photographs. The images of the solar concentrator to be measured are obtained from different viewpoints. The solar concentrator is recreated in three dimensions using the principle of collinearity between reference points (reference targets in the concentrator surface or structure) of the images taken. From this 3D model obtained by photogrammetry, and using ray tracing techniques, the total intercept factor can be obtained.
Deflectometry (or Fringe Reflection Technique, FRT) is and alternative technique to photogrammetry, where normal vector in every surface element of the reflector is computed. The method consists of measuring the reflection of static or dynamic sinusoidal pattern on the reflector, computing the normal vectors from these reflections and calculate the local slope deviations values (Burke et al. 2013; Heimsath et al. 2011; Heimsath et al. 2008). As with photogrammetry, the intercept factor can be calculated with ray tracing using the output normal vectors from the deflectometry method (Andraka et al. 2009; Meiser et al. 2015).
A Guideline for measurement of the solar mirror shape accuracy was drafted by the Solar Paces Task III (SolarPaces Guideline 2013a).

Following figures shows some sample results of linear Fresnel collectors, measured by deflectometry.

a)
b)

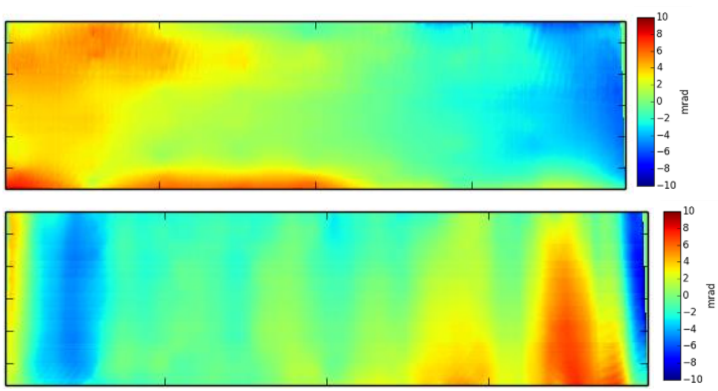

Figure 1: Linear Fresnel Collector mirror maps of local surface slope deviations of a bad mirror. Significant shape errors are visible. 1a, slope deviations in curved direction. 1b, slope deviations in longitudinal direction

Some other techniques use a *laser beam* projected in the reflecting surface. The shape is measured by scanning the panel surface with the laser beam in the direction of curvature and analyzing the direction of the reflected beam. Different devices have been developed based on this technique (Jones et al. 1997; Maccari and Montecchi 2007). In the market there are also laser scanners with enough accuracy/resolution which can be used for shape measurement of solar concentrators.

Independently of the techniques used for the shape measurements, typical output parameters of all these techniques/methodologies, which are of interest to know how accurate is a solar concentrator, are the standard deviations of the reflector slope of the whole reflector (solar concentrator) in both *x* and *y* directions of the solar concentrator, *SDx* and *SDy* respectively. See in Figure 1 an example of angular deviations in the XZ plane of a small sized parabolic trough collector developed in the framework of the CAPSOL project (Fernández-Reche and Valenzuela 2012; Fernández-Reche and

Fernández-García 2009).

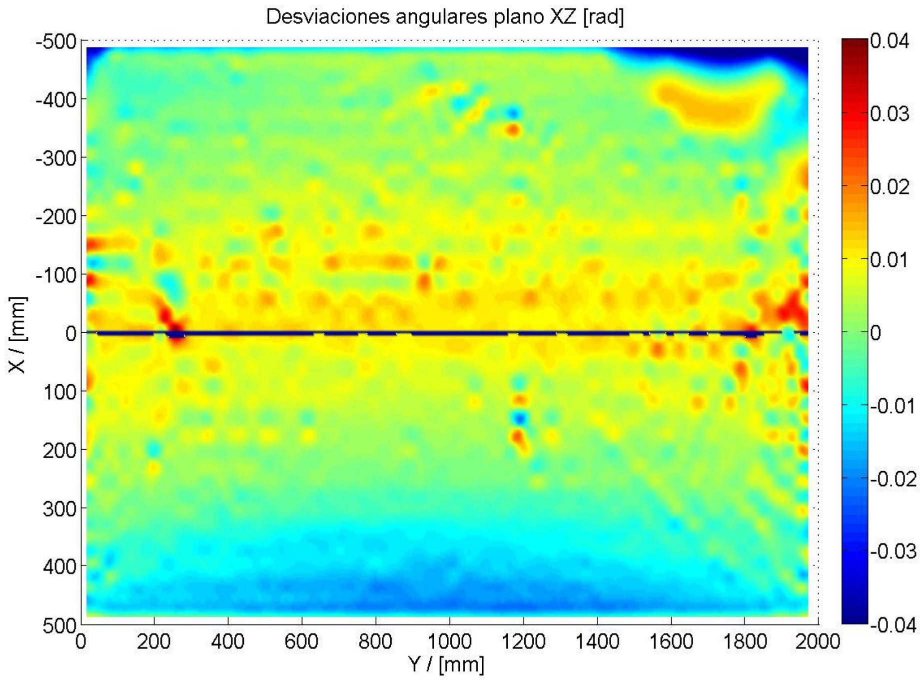

Figure 2: Projection in the XZ plane of the angular deviations to the normal of the CAPSOL PTC prototype (Fernández-Reche and Fernández-García 2009; Fernández-Reche and Valenzuela 2012).

4.4 Solar trackers

Author: F. Sallaberry (CENER)

4.4.1 Definition of a tracking device

The solar-tracker (or sun-tracker) is a device which enables a system to follow mechanically the sun direction in order to minimize the incidence angle of the beam solar radiation. It can be used for photovoltaic panels, reflectors, optical devices such as telescopes, sensors such as pyrheliometers, or a solar thermal collector.

4.4.2 Key parameters future testing methods

According to the standard IEC 62817 (2014) and Mousazadeh et al. (2009), the motorization of the tracker can be achieved by three types of drives:

- Passive drive systems which use differential fluid pressure generated by different shading gradient to drive the tracker axis.
- Active-electric drive systems which transfer electrical energy to electrical motors to create rotational motion
- Active-hydraulic drive systems which use pumps to generate hydraulic pressure which is transferred through valves, pipes, and hoses to a hydraulic motor or cylinder

For the active drive type, there are three main kinds of tracking methods depending on which input data are used to calculate the ideal position of the tracker:

- **Closed-loop control** which uses some sort of feedback (such as a sun position sensor, an encoder, an inclinometer or the power output of the system to be tracking) to determine how to drive the actuators and position the tracker structure. Some electro-optical sensors can be used which produce a differential control signal if the illumination received by the sensors are different. This signal is used to drive the motor and to orient the system in such direction where the illumination of electro-optical sensors becomes equal.
- **Open-loop control** which does not use any feedback but uses mathematical calculations of the sun position (based on the time of the day, the date, the location etc.) to determine where the tracker should be pointing at and drives the actuators accordingly.
- **Hybrid control** which combines the mathematical sun position calculations (open-loop code) with a sun sensor data (used in a closed-loop feedback control).

Solar trackers can also be classified by the number and orientation of the tracker's axis (Mousazadeh et al. 2009). The possible types are:

- **Single axis:** horizontal axis (axis of rotation horizontal in respect to the ground), vertical axis (axis of rotation vertical in respect to the ground), and tilted axis (axis of rotation between horizontal and vertical).
- **Double axis:** the tip-tilt (primary axis horizontal and secondary axis normal to the primary axis) and the azimuth-altitude (primary axis vertical and secondary axis normal to the primary axis.

The tracking of linear concentrator with single-axis could be done according to two different positions: The North-south (N-S) orientation for which the tracking consists in moving in elevation from East to West and the East-West (E-W) orientation for which the tracking consists in moving in elevation from North to South.

According to the standard IEC 62817 (2014) Table 1 – "Tracker specification template, the different characteristics", other specifications should be provided by the manufacture (IEC 62817 2014):

- Payload characteristics (Minimum/maximum mass supported, Payload center of mass restrictions, Maximum payload surface area, Nominal payload surface area, Maximum dynamic torques allowed while moving, Maximum static torques allowed while in stow position)
- Installation characteristics (Allowable foundation, Foundation tolerance in primary axis, Foundation tolerance in secondary axis, Installation effort, Payload interface flexibility)
- Electrical characteristics (Daily energy consumption, Stow energy consumption, Input power requirements)
- Tracking accuracy (Accuracy, typical and 95th percentile)
- Control characteristics (Control algorithm, Control interface, External communication interface, Stow time)
- Mechanical design
- Environmental conditions
- Maintenance and Reliability

4.4.3 Testing of solar trackers

So far, there is no specific standard for the solar tracker testing for solar thermal collectors. In 2014, an international standard IEC 62817 (2014) was published in order to certify solar trackers for PV applications that considers both accuracy and durability, and defines some tests for tracking precision of such devices. But in this standard applicable to PV trackers, the solar tracker for solar thermal applications with single-axis solar tracking is not easily applicable. Thus, this testing methodology had to be adapted for solar thermal trackers, which are mainly single-axis.
In 2015, other standards for PV solar trackers were published, UL 2703 and 3703 (2015), but only for requirements of the tracker installation and is not applicable to optical concentrators.

In this IEC TC 117 committee, one working group has been created in order to define the testing standards for parabolic trough collector (Draft IEC 62862-3-2). One part of the testing methodology is dealing with the solar tracking characterization, using inclinometer for horizontal single-axis solar tracker. This methodology has been recently validated experimentally on medium to high temperature solar thermal collectors and will be published in Sallaberry et al. (2015b) and Sallaberry (2015).

5 Collector testing

5.1 Literature overview

Author: Annie Hofer (FHG-ISE)

A multiplicity of publications exists in the area of testing solar thermal collectors, research and development has been performed for years. A literature review has been conducted by Hofer et al. (2015b) focusing on testing and evaluation procedures for tracking concentrating collectors. Figure 3 summarizes published evaluation methods in this context.

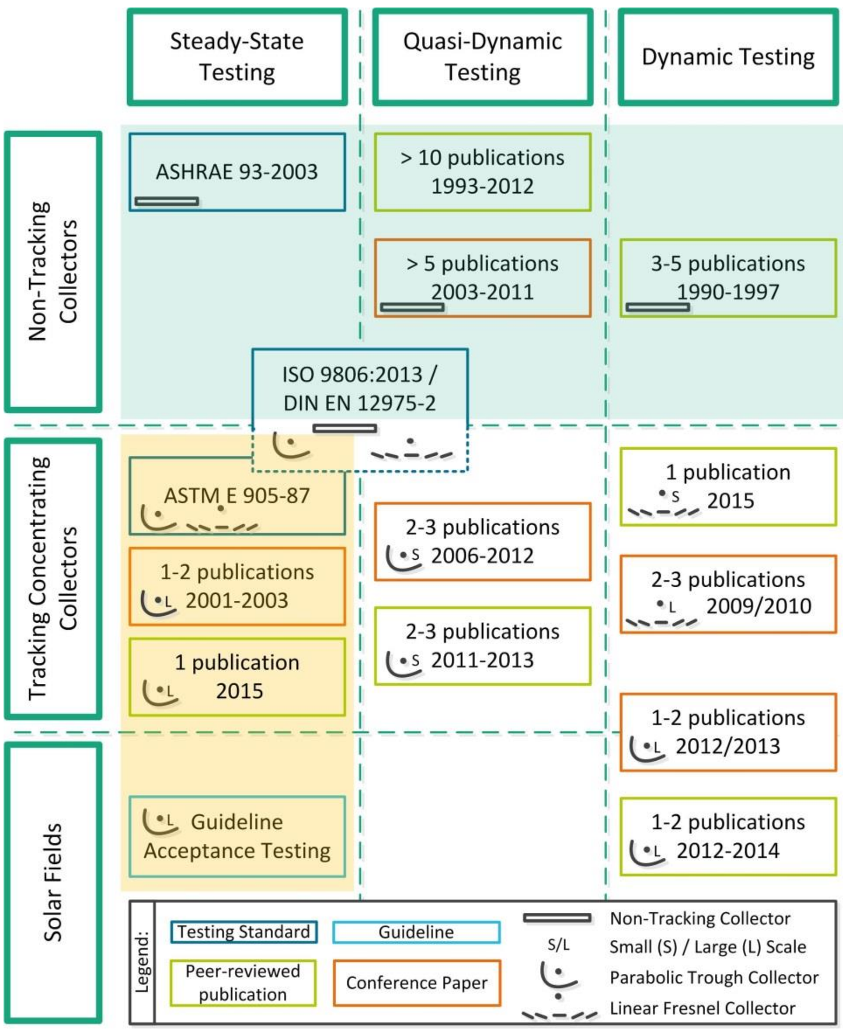

Figure 3: Summary of published testing and evaluation procedures with focus on concentrating solar collectors (Hofer et al. 2015b)

"The publications with their respective testing procedures were differentiated into two aspects: their testing methodology on the one hand side and their application on the other hand side, allowing a more structured and traceable comparison of the different testing methods. In Figure 3 the detailed literature review is summed up according to the introduced categories. The methodologies are grouped into steady-state (SST), quasi-dynamic (QDT) and dynamic (DT) testing, whereas the application of the published testing procedures are classified into non-tracking (stationary) collectors,

tracking concentrating collectors and large solar fields of tracking concentrating collectors.

It shows that the majority of publications in the field of collector testing are dealing with non-tracking collectors. In this area a multiplicity of diverse testing and evaluation procedures has been published. […] Especially the quasi-dynamic testing procedure was investigated, adapted and applied in several publications for different technologies, mainly based on the work done by the research group of Perers (e.g. see Perers (1997)). Moreover the QDT-method presents part of the basis of the current testing standard ISO 9806 (2013) and other standards (see Kramer et al. (2011)). As a counterpart to the QDT-procedure the dynamic testing method has firstly been introduced by Muschaweck and Spirkl (1993), containing a more sophisticated collector simulation tool, but less restriction in measurement data (Muschaweck and Spirkl 1993). The QDT-method is based on a linear collector equation and quite strict boundary conditions, which allow the use of multiple linear regression (MLR). In contrast the DT-method is based on different kinds of specific (dynamic) collector simulation models allowing a more flexible combination with an optimization algorithm consisting for example of a non-linear least-squares (NLS) minimization approach. A comparison of both mathematical approaches by Fischer et al. (2003) showed that they are equivalent in their results, NLS minimization only being more flexible (Fischer et al. 2003).

In the area of tracking concentrating collectors there does exist an American testing standard ASTM E 905-87 based on steady-state testing (ASTM E 905 – 87 1987 (Reapproved 2007)). […] An approach of steady-state testing has been applied for measuring the performance of large parabolic-trough collectors (L. Valenzuela, R. López-Martín, E. Zarza 2014). […] Nevertheless these testing procedures are either very time consuming or (if not the latter) mostly not comprehensively characterizing the collector or field performance, as they are limited to particular conditions (high DNI, normal incidence at solar noon etc.).

In Figure 3 the testing standard ISO 9806:2013 is marked with dotted lines in the area of tracking concentrating collectors, as it is not fully applicable to all concentrating collectors without modifications. Publications in this field show, that the QDT-method is successfully applied particularly for small-scale parabolic trough collectors (marked with an S), as restrictions to measurement conditions can still be met (see Fischer et al. (2006) and Janotte et al. (2009)). For a global characterization of large-scale collectors (marked with an L), either parabolic trough or linear Fresnel, mainly the dynamic testing method is applied, as with higher working temperatures, energy loads to be cooled to meet stationary inlet conditions cannot easily be fulfilled. In particular for the characterization of linear Fresnel collectors due to their special optical characteristics in terms of a two-dimensional IAM, new approaches by dynamic parameter identification (Platzer et al. 2009; Hofer et al. 2015a), or modifications to the QDT-methods are inevitable (compare with (Hofer et al. 2015a)). […] Quasi-dynamic testing is rarely applied to large collectors or solar fields, which might be an indication, that the QDT-method with its restriction in measurement data is not entirely suited for the performance evaluation of larger systems. A guideline focusing on characteristics, assets and drawbacks as well as practical indications for the use of dynamic solar collector and solar field performance testing is currently being compiled (see Hofer and Janotte (2015/16)).”

5.2 General aspects

Author: Sven Fahr (FHG-ISE)

In a broader sense, the aim of any efficiency testing procedure is to offer the possibility to predict the expected energy yield of the product at any position in the world using its respective set of weather data. To be able to do so, a generally valid and comprehensive parametrization of the collector is required. Furthermore, it is important to characterize the collector in a commonly accepted or even better standardized way, in order to receive results useful for inter-comparison.

As in solar process heat, different collector technologies compete against each other, it is important to be aware that there may be differences in the way they have been tested, in the type of irradiance that the results refer to and the plane it has been measured in, respectively. Moreover there may be differences in the definition of the energy collecting surface, in the model equation and even in the definition of the individual parameters used to describe the power output. When comparing different possibilities it is to be noted that specific parameter values may not be comparable without prior adjustment or transformation.
Inter-comparison is relatively simple for rather conventional technologies as standard flat plate collectors (FPC) or evacuated tubular collectors (ETC), as the most relevant current testing standard ISO 9806:2013 gives detailed instructions on the procedures and framework to characterize these types of collectors and the regulations have been applied commonly for years.
Difficulty of comparison increases, as soon as more complex technologies come into play, starting from booster reflectors over stationary compound parabolic concentrators (CPC) to the technologies of PTC and LFC. Due to their very small market share and the high complexity of their characterization procedures, solar air heating collectors will not be considered specifically in this guideline. Readers particularly interested in this technology are advised to perceive the publications (Stryi-Hipp et al. 2011; Kramer 2013; Kramer et al. 2014).
In the following chapters state-of-the-art testing methodologies shall be described shortly with focus on their differences, the technologies they are addressing and their advantages and disadvantages. Special attention will be given to the problem of different definitions of irradiance measurement in the fields of concentrating and non-concentrating collectors, the incidence angle modifier (IAM) and new leads as well as alternative methodologies apart from the current testing standard.

5.3 Referenced irradiation

Author: De Wet van Rooyen (FHG-ISE)

The referenced irradiation required for calculation of the optical (and eventually thermal) yield may very well differ depending on the collector type being tested. In order to interpret an expression of optical efficiency (of a collector) the corresponding referenced irradiation and reference aperture surface must be known. Lists are given below followed with a description of each entry.

The following reference plane **orientations** are used depending on collector type:

- **Collector plane:** Defined for each collector individually.
- **Collector aperture plane:** Defined for each collector type individually
- **Effective aperture plane:** A plane perpendicular to the incoming solar beam.
- **Horizontal plane:** A plane in the horizontal orientation.

The corresponding reference plane **surface areas** are used:

- **Gross area:** area based on the max. dimensions of the collector, without connections
- **Aperture area:** The solar energy capturing area by definition.
  - For LFC: Defined as the net mirror area of the collector.
  - For PTC : Defined as the product of trough opening width and trough length
  - For flat collectors: area through which beams can enter the collector interior. Formerly the basis for efficiency values, since the publication of the current ISO 9806 :2013 all efficiency values are referenced to gross area
- **Effective aperture area** at a given initial sun position:

- In general this is the projection of a surface area in a specified plane onto the plane perpendicular to the solar beam

$$A_{eff} = A * \cos(\theta), \quad \text{Eq. 1}$$

where θ the incidence angle of the solar beam on the specified plane, A the area in the specified plane and A_{eff} the effective area.
- For LFC: Defined as the net mirror area of the collector projected onto the horizontal along the solar beam when the sun is at its zenith and the mirrors are in their tracked positions.

The following **reference irradiation** used for different collector types can be found in the list below:

- **G – Global irradiation:** Measured with a horizontal sensor or in the collector aperture plane.
- **DNI – Direct Normal Irradiation:** Radiation incident on a plane perpendicular to the solar beam, and originating from a small solid angle centered at the sun's disk. Measured with a sun-tracked pyrheliometer.
- **G_d – Diffuse solar irradiation:** Measured with a shaded pyranometer under a shadow ring, tracking ball or rotating shadowband.
- **G_b – Direct solar irradiation:** calculated as

$$G_b = G - G_d \quad \text{Eq. 2}$$

or for short intervals

$$G_b = DNI * \cos(\theta) \quad \text{Eq. 3}$$

For concentrating collectors the DNI is the most relevant reference irradiation. The so-called ‘diffuse acceptance’ is low, meaning that the diffuse component of the global irradiation does not contribute to the yield. It is thus all the more important to understand the nature of the DNI irradiation of consideration in concentrating collectors. The position of sun in combination with atmospheric influences causes the solar disc to change its perceived size. An image will thus also change its size. From Rabl (Rabl 1976) the average radial distance is 4.65 mrad (0.266 °). Furthermore, the beam radiation is scattered in various atmospheric conditions to such an extent that not all the beam radiation is seen as coming from the solar disc itself, but rather from the so-called “circumsolar region", the region around the sun from 4.65 mrad to 50 mrad (Rabl 1976). The Circumsolar Ratio (CSR) expresses the fraction of beam radiation, which is perceived to come from the circumsolar region.

$$\mathrm{CSR} = \frac{\text{Circum Solar Radiation}}{\mathrm{DNI}}, \quad \text{Eq. 4}$$

The intensity distribution of the radiation of the solar disc and circumsolar region is what we call the “sunshape". For different CSR, different sunshape descriptions are available (Neumann et al. 2002). The relative intensity over the solar disc and circumsolar region is plotted for three circumsolar ratios in Figure 4.

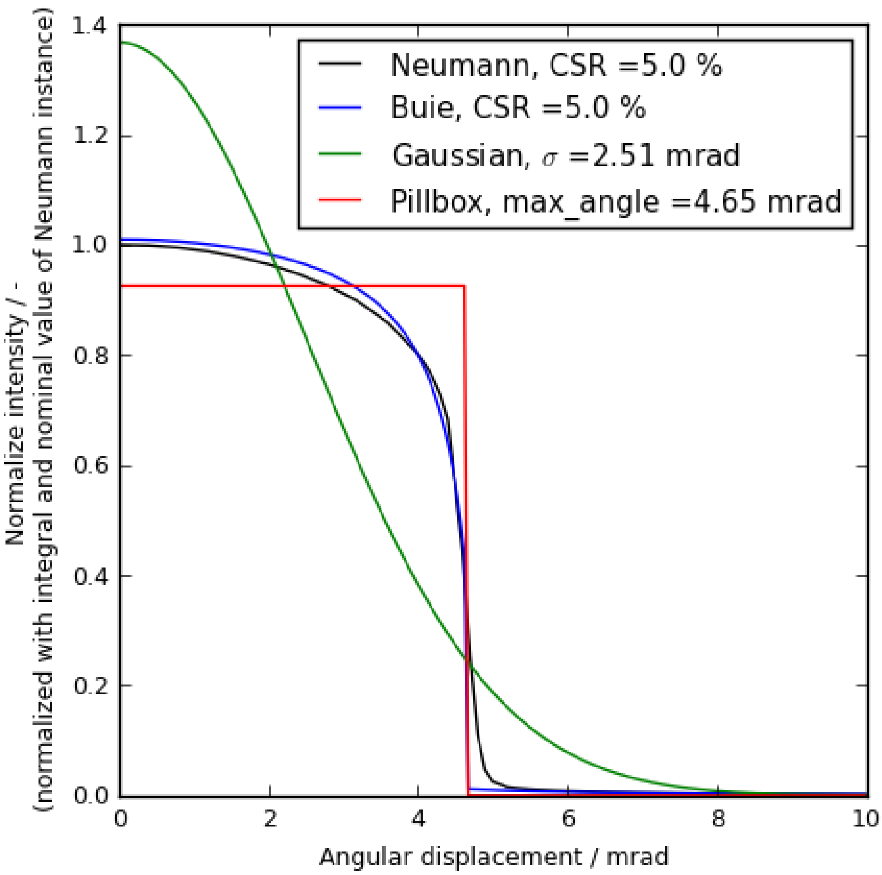

Figure 4: Circumsolar ratio relative intensity

It is important to consider the sunshape when studying imaging concentrating solar collectors, as the produced image at the absorber has an effect on the optimal operating temperature, acceptance angle of a possible secondary reflector, receiver aperture size and eventually the overall efficiency of the system (Buie and Monger 2004; M. Schubnell 1992).

Some untracked, low concentrating collectors however have a diffuse acceptance which cannot be neglected. Studies by (Hess and Hanby 2014) have shown that considering the diffuse irradiation as anisotropic (in comparison to isotropic) in simulations of collector yield deliver a closer fit to reality.

5.4 Efficiency testing methodologies

Authors: Sven Fahr (FHG-ISE), Annie Hofer (FHG-ISE)

ISO 9806:2013 includes two standardized efficiency testing methodologies, the steady-state testing (SST) method and the quasi-dynamic testing (QDT) method. Both methods have originally been developed to characterize non-concentrating and low temperature thermal collectors and since merging with EN12975-1:2006-A1:2011 concentrating collectors are explicitly included in the scope of the standard. Until today, both normative approaches and their regulations have not been optimized for concentrating collectors and the standard gives specific instructions only for the usage of water as HTF and only up to a maximum temperature of 185°C and a maximum pressure of 12bar. Nevertheless, the QDT method has been successfully applied to PTC and other concentrating collectors (Janotte et al. 2009; Fischer et al. 2006; Fahr et al. 2012) and developed beyond the standard procedure to even be applicable to LFC (Hofer et al. 2015a). This chapter shortly describes the standard methods and, additionally, a non-standard fully dynamic testing procedure, which has been developed and successfully applied by Fraunhofer ISE. Specifics considering the determination of the IAM of LFC, combining ray tracing simulations and experimental data, will be given in chapter 5.5.4. Unglazed collectors are not considered in this guideline, as they seem unlikely to be used in process heat applications.

5.4.1 Steady-state test method according to ISO 9806:2013

Description

The steady-state method sets very strict limitations to all process conditions within the test sequences, the limits are to be found in Table 5.

Parameter	Limit	Max. variation
G	>700 W/m²	+/- 50 W/m²
G_d/G	<30%	
θ	$\lvert IAM_\theta - IAM_{0°} \rvert < 0.03 \times IAM_0$	
Ambient air temperature		+/- 1.5 K
u	3 m/s +/- 1 m/s	
Fluid mass flow rate		+/- 1 % within sequence +/- 10 % between sequences
Collector inlet temperature		+/- 0.1 K
Collector outlet temperature		+/- 0.5 K
$T_{out} - T_{in}$	>1K	

Table 5: Acceptable variations in process parameters (ISO 9806 2013)

These restraints make it possible to operate the collector in a defined operating point, making it possible to easily determine instantaneous power output and collector efficiency. In doing so for different inlet temperatures evenly distributed over the operating temperature range of the collector, the efficiency curve of the collector in dependency of the temperature can be determined. In combination with the determination of the incidence angle modifier (IAM) by measuring the collector efficiency at $T_{mean} = T_{amb}$ and under specific incidence angles, the instantaneous efficiency can then be described as

$$\eta_{hem} = \eta_{0,hem} \cdot K_{hem}(\theta_l, \theta_t) - a_1 \cdot \frac{(\vartheta_m - \vartheta_a)}{G} - a_2 \cdot \frac{(\vartheta_m - \vartheta_a)^2}{G} \qquad \text{Eq. 5}$$

where ϑ_m is the medium fluid temperature, ϑ_a the ambient temperature and G is the global hemispherical irradiance.

Table 6 explains the significance of the individual collector parameters and their units. The collector thermal capacity can be calculated from the collector components or by an additional test, for details on the topic IAM see chapter 5.5.

Parameter	Significance	Unit
η_{hem}	Collector efficiency, with reference to *T**m, based on hemispherical irradiance G	-
$\eta_{0,hem}$	Peak collector efficiency (η_{hem} at T*m = 0), reference to T*m, based on hemispherical irradiance G	-
T^*m	Reduced temperature difference ($=(\vartheta_m - \vartheta_a)/G$)	m^2K/W
$K_{hem}(\Theta_l, \Theta_t)$	Incidence angle modifier	-
Θ_l	Incidence angle in longitudinal plane, compare chapter 5.5	°
Θ_t	Incidence angle in transversal plane chapter 5.5	°
a_1	Heat loss coefficient at $(\vartheta_m - \vartheta_a)$= 0	$W/(m^2\cdot K)$
a_2	Temperature dependence of the heat loss coefficient	$W/(m^2\cdot K)$

Table 6: Collector parameters of steady-state equation (ISO 9806 2013)

Note that this model does not distinguish between direct and diffuse irradiation and explicitly accounts neither for wind dependencies nor thermal radiation effects. Thus, its results are strictly speaking only valid for the ambient conditions under which they were obtained and the method is only applicable to collectors which are insensitive to those influences. While there are means to theoretically calculate from these results also separate parameters for beam and diffuse irradiation, note that these can only be approximations. For the characterization of concentrating collectors the standard requires the use of QDT, unless a distinction between diffuse and beam irradiance is taken into account also for SST (ISO 9806 2013).

Scope of collector types
Although the SST method is admitted also for concentrating collectors when beam and diffuse irradiance are separated, it is recommended to only use it for the following collector types:

- Standard glazed FPC
- Standard ETC

Advantages and disadvantages

Pro	Con
Errors easily detectible	Strict limits to ambient conditions
Long experience	Results specific to measurement conditions
High repeatability	Less differentiation
Fast in case of good ambient conditions	Time effort in moderate climate areas
Little computational and supervision effort	Applicability to collector technologies other then FPC and ETC
Indoor testing possible	

Table 7: Advantages and disadvantages of SST

5.4.2 The quasi-dynamic test method according to ISO 9806:2013

Description
As against the steady-state method, the QDT method sets no general limits to any ambient conditions, only the variation of the process parameters, inlet temperature and mass flow, is restricted. As beam, diffuse and thermal irradiance, incidence angle, ambient temperature and wind velocity vary almost randomly, steady operating points are not to be reached. In the contrary, varying instantaneous power outputs are recorded together with the ambient conditions influencing it, making it possible to analyze the transient behavior of the collector. By recording data under a wide range of ambient conditions fluctuating independently of each other, it is possible to separate the individual influences and

describe their impact on the power output with parameters. Since many more influences have to be accounted for than in SST, the QDT uses the more detailed model equation

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} \cdot K_b(\theta_t, \theta_l) \cdot G_b + \eta_{0,b} \cdot K_d \cdot G_d - c_6 \cdot u \cdot G - c_1 \cdot (\vartheta_m - \vartheta_a) - c_2 \cdot (\vartheta_m - \vartheta_a)^2 - c_3 \cdot u \cdot (\vartheta_m - \vartheta_a) + c_4 \cdot \left(E_l - \sigma \cdot T_a{}^4\right) - c_5 \frac{d\vartheta_m}{dt} \qquad \text{Eq. 6}$$

where A_G is the gross collector area, G_b is beam irradiance, G_d is diffuse irradiance, u is wind velocity, E_l is downward longwave irradiance and σ is the Stefan-Boltzmann constant.
Table 8 explains the significance of the individual collector parameters and their units (ISO 9806 2013).

Parameter	Significance	Unit
$\dot{Q}_{out\_col}$	Useful power extracted from collector	W
$\eta_{0,b}$	Peak collector efficiency (η_b at T*m = 0), reference to T*m, based on beam irradiance Gb	-
T*m	Reduced temperature difference (= $(\vartheta_m - \vartheta_a)$/G)	m^2K/W
$K_b(\Theta_l,\Theta_t)$	Incidence angle modifier for direct radiation	-
K_d	Incidence angle modifier for diffuse radiation	-
c_1	Heat loss coefficient at $(\vartheta_m - \vartheta_a)$= 0	$W/(m^2 \cdot K)$
c_2	Temperature dependence of the heat loss coefficient	$W/(m^2 \cdot K)$
c_3	Wind speed dependence of the heat loss coefficient	$J/(m^3 \cdot K)$
c_4	Sky temperature dependence of the heat loss coefficient	-
c_5	Effective thermal capacity	$J/(m^2 \cdot K)$
c_6	Wind dependence in the zero loss efficiency	s/m

Table 8: Collector parameters of quasi-dynamic equation (ISO 9806 2013)

The full collector model is detailed enough to describe most collector models on the market. Whether a specific parameter is relevant or not can be decided with respect to the results of the parameter identification. While some parameters are mandatory others can be excluded, if they prove to have no statistical relevance (T-Ratio < 3). Although the standard allows for some collector types to exclude certain parameters from the beginning, it is recommended to always start parameter identification with the full model and rule out irrelevant parameters by relevance (ISO 9806 2013).

The recorded data matching the given restrictions is used to characterize the test sample by means of parameter identification. The standard suggests using multi-linear regression which is a non-iterative fast matrix method, mainly because it is available in most standard software with statistical functions, but other methods such as iterative procedures are also acceptable. Extended MLR analysis methods have been presented, which allow even the detection of multiple dependencies of a parameter (Perers 1997; Fischer et al. 2004). The parameter identification works by minimizing the calculated output power of Eq. 6 versus the measured collector output, determining all parameters at the same time and from the same set of data. Accordingly, to minimize correlations between parameters it is crucial to select a data representing enough variability in all relevant input variables.
As opposed to the SST, the QDT incorporates more physical interrelations and processes much more diverse measurement data and is therefore commonly thought to produce more realistic and generally valid parameters. To compare SST and QDT results, power outputs have to be calculated for a specific set of ambient conditions.

Scope of collector types
As the above mentioned model considers more individual influences on collector efficiency it is also suitable to more kinds of different collector technologies, which are sensitive to these influences e.g. concentrating collectors. Note, that QDT in the very way described in the standard is not suitable to

properly characterize the optics of regular LFC installations because, usually, the necessary combinations of different longitudinal and transversal incidence angles are impossible to realize. Remedy can be found in the combination of QDT with iterative procedures, compare chapter 5.5.5.
QDT with standard or extended MLR tools is recommendable for:

- Standard flat plate collectors
- Standard evacuated tubular collectors
- Low concentrating collectors, e.g. CPC
- Highly concentrating collectors, e.g. PTC, LFC
- PVT-collectors

Advantages and disadvantages

Pro	Con
High differentiation of influences	Required incidence angles may be impossible to realize for certain line-focusing installations
More realistic and generally valid results	Not easily applicable in case of bi-axial IAM behavior
All parameters within one measurement	Bigger computational and supervision effort
Time effort in moderate climate areas	Few weather dynamics in sunny climate areas
Applicability to collector technologies	Limited variation of inlet temperature and mass flow

Table 9: Advantages and disadvantages of QDT

5.4.3 Dynamic testing method

As QDT is still using a steady-state approach in terms of power output calculation and a linear collector equation, it works with averaged values of usually 5 to 10 min periods and is strictly speaking not analyzing transient behavior in short time steps. This is also the reason for the limitations in variation of inlet temperature and mass flow. The dynamic testing (DT) method is free of these restraints, and its functionality has been described and compared to QDT results in (Hofer et al. 2015a):

"Measurement data of the collector are compared to simulation data generated by a dynamic collector simulation model. In dependence on measured input quantities of the collector (like inlet temperature, inlet pressure, inlet mass flow), including weather data (like G_b, wind velocity etc.) and fluid properties, outlet quantities of the collector are simulated, incorporating optical and thermal performance parameters on the basis of a dynamic collector model. The simulated output is then compared to measured collector output. Based on the deviation of simulated data to measured output data, performance parameters (in Figure 5 so-called model parameters) are adapted by means of an optimization algorithm. Simulated collector output data is recalculated in dependence on the new set of model parameters generated by the optimization algorithm. This iterative procedure is performed until the root mean square of the difference between measured and simulated data reaches a minimum and data coincides best.
The performance parameters corresponding to this minimum represent the final performance parameters of the collector derived from the given set of measurement data."

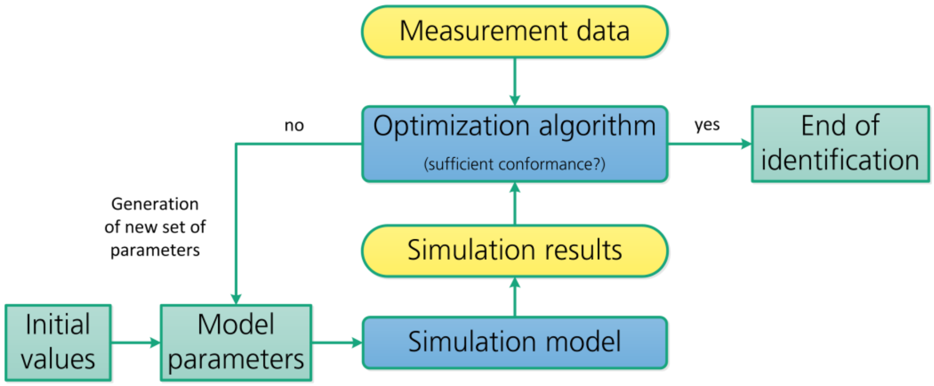

Figure 5: Sketch of the dynamic parameter identification method (Hofer et al. 2015a)

In the guideline "Dynamic in situ Performance and Acceptance Testing of Line-Concentrating Collectors and Solar Fields" currently under publication and written within the German project StaMeP, the differences and advantages in comparison with QDT have been described (see *Hofer and Janotte (2015/16)*):

"Theoretically, also the QDT-method could make use of the parameter identification method sketched in Figure 5. In this case the collector simulation model would be represented by the one-node collector equation [Eq. 6 presented in 5.4.2]. As the objective of the present approach is the evaluation of the dynamic performance of a collector, the simulation model should not be based on a steady-state approach but reproduce the dynamic behavior of a collector. Therefore, any dynamic simulation model can be used, mostly incorporating a discretization of the (simplified) Navier-Stokes equations. In most cases a compromise between accuracy of the simplifications and discretization method as well as calculation time has to be found.

The big advantage of the DT-method over the QDT-method is the higher flexibility in the evaluation routine. With the dynamic parameter identification method the evaluation procedure is not restricted to fulfill the steady-state and linear collector equation of the QDT-method. Therefore neither the inlet temperature nor the mass flow has to be kept constant, apart from accepting any variation of the irradiance. As a consequence it is possible to include periods of warm-up and cool-down into the performance evaluation. Mostly whole days from sunrise to sunset may serve as a suitable data set, leading to the option of significantly reducing the number of measurement days. Moreover the flexibility of the dynamic parameter identification method is allowing a direct assessment of the biaxial (two-dimensional) IAM-matrix of a linear Fresnel collector. The values of the IAM along the transversal and longitudinal axis can be read in and be optimized automatically. "

The parameter identification tool used in the DT method is generally approved by the standard and has shown equivalent results in both cases of same and similar/comparative measurement data basis (Hofer et al. 2015a). Combined with the vaster degrees of freedom, it must be considered to be the most promising and powerful tool for the characterization of LFC and in situ measurements in general. Nevertheless, it is not yet a normative described procedure and there are several gaps to be closed. The DT method uses outlet temperature as figure of merit, while the testing standard demands to minimize the error in output power. Moreover, commonly agreed collector models and regulations are missing to assure equivalent results independent of the executing measurement body.

Scope of collector types

Although it is potentially applicable to all collector types, it has been developed and is currently optimized for line-focusing collectors:

- LFC
- PTC

Advantages and disadvantages

Pro	Con
No limitations in process variables and system operating	Not standardized
Determination of biaxial IAM for discrete angles	Higher computational effort
Potentially less time effort	
Potential for in situ measurement and field tests	

Table 10: Advantages and disadvantages of DT

5.5 Incidence Angle Modifier

Authors: Tiago Osório (University of Évora), Dr. Pedro Horta, (FHG-ISE)

5.5.1 General aspects

Calculation of the instantaneous power of a solar collector under prescribed irradiation and operation conditions (and thus of its energy yield over a given period) requires special care in the consideration of how collector optics affect the absorbed solar radiation.
Not only the optical properties of the materials used, but also the path taken by the incident rays between the aperture of the solar collector and the absorber surface are dependent on the incidence conditions. Hence, the optical performance of a collector depends on its material and geometrical features and requires a duly incidence angle dependent characterization.
Collectors presenting a rotational symmetry with respect to the aperture surface normal, such as flat plate collectors (FPC), are easy to characterize from an optical point of view. In contrast, collectors presenting a biaxial geometry, such as evacuated tubular collectors (ETC), stationary or quasi-stationary line-focus concentrators (e.g. compound parabolic concentrator– CPC) or one axis tracking line-focus concentrators (parabolic troughs – PTC, or linear Fresnel reflector collectors– LFC) require the incident radiation to be decomposed in its direct and diffuse components and treated in, at least, two orthogonal planes, for proper account of the optical effects that are common in these devices.
The Incidence Angle Modifier (IAM) reflects the impact of incidence dependent optical and geometrical properties of the solar collector on its absorbed irradiance. Considering the varying incidence conditions to which (one-axis tracking and stationary) solar collectors are subjected, it is thus essential for long term energy calculation.
The present chapter aims at presenting state-of-the-art IAM definitions and measurement procedures as well as at identifying shortcomings in the present standardized procedures, introducing suggestions to overcome them.
Following the definitions of the collector model introduced in chapter 5.4, the current version of ISO 9806:2013 is taken as reference document in this analysis. In spite of the efforts taken on its last revision to enable its adoption in the testing of solar concentrating technologies, some questions are still pending of deeper definition at both experimental procedures and collector modelling levels. A paramount question is the need of separating end loss effects from the IAM and introducing a collector (longitudinal) length dependent end loss effect function for collectors to be installed in rows. Chapter 5.5.3 will cover this subject while chapter 5.5.4 is dedicated to the proposal of using ray tracing software tools to complement experimental results and thus alleviate the standard requirements regarding imposed incidence conditions.
Considering the scope of IEA Task 49 only glazed collectors or unglazed concentrating collectors with $C > 10$ are herein considered.

5.5.2 Definitions and standard measurement procedures

The zero thermal losses efficiency at normal incidence of a solar collector (sometimes referred as peak efficiency[5] or optical efficiency), η_0 (see Eq. 5 and Eq. 6), is measured at normal incidence and accounts for manifold optical effects affecting the optical performance of the solar collector, such as:

- optical properties of reflectors (ρ), glazing (τ, n) and absorber (α);
- specular reflection deviations (σ_{spec});
- sun shape effects (σ_{sun});
- manufacturing deviations (from theoretical optical design).

The IAM, accounting for incidence angle dependent variation of optical effects, is defined as the ratio of the efficiency at a prescribed incidence angle and the efficiency at normal incidence where both efficiency values are defined at zero thermal losses conditions:

$$K(\theta) = \frac{\eta_0(\theta)}{\eta_0} \qquad \text{Eq. 7}$$

It includes effects such as:

- angular variation of optical properties of reflectors (ρ), glazing (τ) and absorber (α);
- angular variation of optical path (average number of reflections <n>, refraction);
- end losses;
- angular variation of the effective aperture area;
- tracking inaccuracies.

In this scope, the incidence angle θ is defined as the angle between the direction of sunlight and the normal direction of the collector.

According to their behavior in relation to the angle of incidence, it is possible to distinguish three types of collectors: isotropic, biaxial and multi-axial. In Figure 6 a system of coordinates is presented, formed by two directions in the plane of the collector and by its normal direction. For a biaxial (or-multi-axial) collector, the longitudinal direction contains the axis of the (tubular) absorber; for a line-focus concentrator, concentration exists only in the transversal plane. The longitudinal angle of incidence, θ_L, is the angle between the direction normal to the collector and the projection of the sun's position into the longitudinal plane. In the same way, the transversal incidence angle, θ_T, is obtained by the projection into the transversal plane. θ_i is the angle defined by the incidence vector and its projection on the transversal plane.

[5] ISO9806:2013 uses the term peak efficiency although a solar collector may have its peak efficiency at a non-normal incidence.

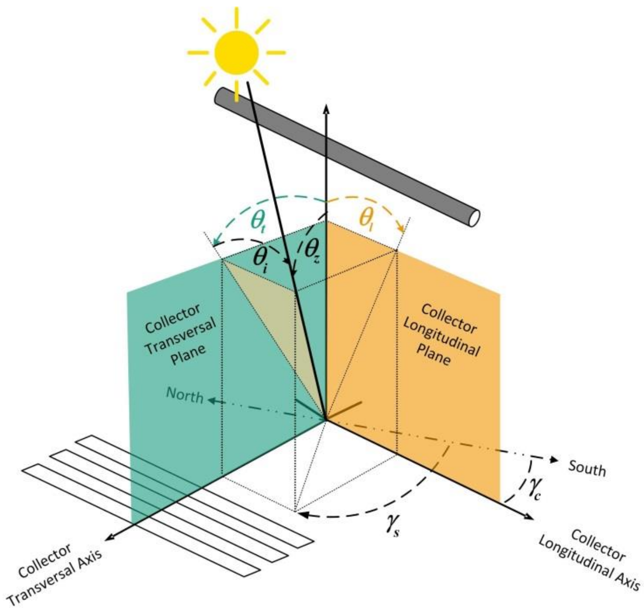

Figure 6: Transversal and longitudinal directions and plans of the collector (Hofer et al. 2015a)

For an isotropic collector, the efficiency is independent of the direction of the incident radiation, which applies to most flat plate collectors. Thus, the behavior of the collector can be modeled by an IAM that only depends on the angle of incidence as described in Eq. 7.
The simplest equation for the IAM, which applies to collectors with isotropic behavior, is given by Eq. 8, with the parameter b_0 adjusted to experimental data:

$$K(\theta) = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \quad \text{Eq. 8}$$

However, this model does not apply to all isotropic collectors, for example to flat plate collectors with transparent insulation (TIM).
Biaxial collectors respond differently to radiation parallel to the longitudinal axis or parallel to the transversal axis. However, they are symmetric with respect to transverse and longitudinal planes. The most common examples of biaxial collectors are evacuated tubular collectors or line-focus concentrators (CPC, PTC or LFC), for which the IAM is a function of both longitudinal and transversal incidence angles and takes the form

$$K(\theta_T, \theta_L) = \frac{\eta_0(\theta_T, \theta_L)}{\eta_0} \quad \text{Eq. 9}$$

If the behavior of a biaxial collector is uncorrelated or weakly correlated over the longitudinal and transversal directions it is sufficient to characterize these two incidence angles in independent tests This approach was proposed in the 80’s by McIntire (McIntire 1982) and it considers that the IAM over each of the directions is independent and the IAM at an arbitrary incidence angle is just the product of the two values. This model was adopted in the standards and it’s commonly used for ETC.

$$K(\theta_T, \theta_L) = K(\theta_T = 0, \theta_L).K(\theta_T, \theta_L = 0) \quad \text{Eq. 10}$$

For more complex optical systems even if they present a biaxial symmetry like CPCs or LFCs the model falls short (Rönnelid et al. 1997). Better results for LFCs have been obtained if the longitudinal incidence angle (θ_L) is replaced with θ_i (Mertins 2009). In Figure 7 the differences between the two models can be clearly observed for an exemplary LFC. In this case the real surface (obtained by ray-tracing) is not shown as it is indistinguishable from the θ_i approximation.

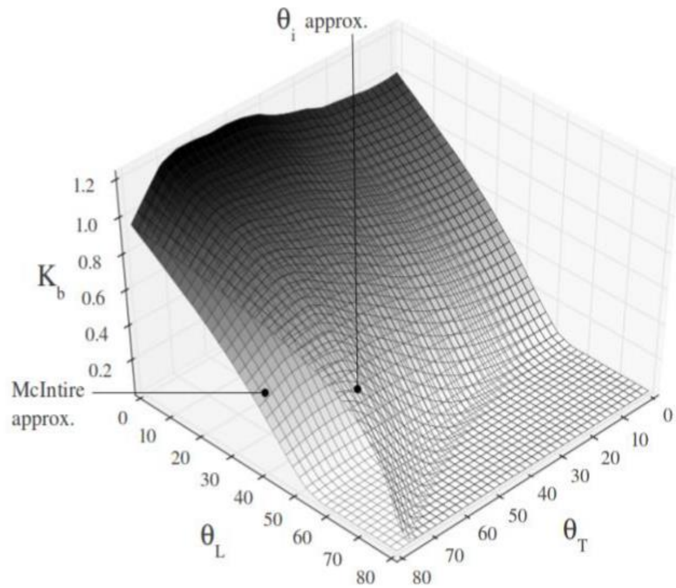

Figure 7: Composed IAM approximations obtained after McIntire and θ_i approaches for a LFC (Horta and Osorio 2013)

For multi-axial collectors there is no symmetry in the longitudinal, transversal, or in both directions. In this case, the IAM function has to take into account all relevant directions for the angle of incidence.
Thus, the methodology generally applied to all types of collectors is to fill a table with experimental points for various angles and interpolate the desired value through the adjacent values. The number of points required depends on the complexity of the IAM. The parameter identification technique (MLR) can easily cope with this by the use of the extended MLR (Perers 1997).

As introduced in chapter 5.4, ISO9806:2013 includes two different solar collector models and corresponding experimental procedures, which can be used in the determination of optical (and thermal) collector characterization parameters: the steady-state and the quasi-dynamic models. A fundamental difference exists in terms of the way irradiance is handled: in the steady-state model global irradiance is used to determine the IAM according to Eq. 7 in at least three points and interpolate in-between them (and the model applies only when diffuse radiation fraction is under 30%). In the quasi-dynamic model, beam and diffuse radiation components are decoupled and the obtained IAM values are, thus, generally valid for all irradiation conditions. Moreover, the IAM for beam irradiation is being determined based on measurement data with a broader range and higher resolution of incidence angles, using either a model equation suiting the collector's optics, e.g. Eq. 8, or the extended MLR if no suitable IAM-model exists.
For the QDT, Eq. 11 defines the IAM in terms of beam irradiance based peak efficiency:

$$K_{\theta b}(\theta_T, \theta_L) = \frac{\eta_{0,b}(\theta_T, \theta_L)}{\eta_{0,b}} \qquad \text{Eq. 11}$$

The IAM for diffuse radiation can be theoretically approximated from hemispherical integration of Eq. 9

(Hofer et al. 2015a; ISO 9806 2013). This term accounts for the collector use of radiation other than beam radiation. The higher the concentration ratio is, the lower is the use of the diffuse component of solar radiation. ISO 9806:2013 includes a method – "Steady state to QDT conversion" – to estimate the quasi-dynamic IAM parameters from steady-state test data (ISO 9806 2013).

In both SST and QDT the reference plane for irradiance measurements (or calculations) is the collector aperture plane. Values of G, G_b and G_d represent a normal incidence at the collector. The relation between direct irradiation and direct normal irradiation (DNI), where 'normal' means a plane orthogonal to the solar vector, is given by Eq. 2.

This means that the IAM as defined in the standard does not include the so called "cosine effect" because this effect is already included in the irradiation values (referred to the aperture plane). As opposed to that, efficiency and IAM measurement on concentrating collectors are often referred to DNI and do include the cosine effect, which is not strictly normative but eventually just an alternative way to present the same result, highlighting that only direct irradiation is used by this type of collectors.

When applying the ISO 9806 test method for linear-focus concentrators, the full IAM characterization for a PTC mounted in the East-West direction is simple to accomplish but is almost impossible for some types of collectors. The LFC is the most obvious example since it has the reflector axis installed horizontally. To fulfil the standard requirements the collector's structure must be tilted in a way that at solar noon the incidence is in normal direction as it is done for flat-plate or any kind of non-concentrating collector. Another approach would be the combination of ray tracing simulations and empirical data as will be explained in chapter 5.5.4.
For a point-focus collector there is no problem since it has a 2-axis tracking mechanism.

It is beyond the scope of this report to go throughout all the different collector models described in the specialized literature. As an example, for PTCs the IAM is often described by a polynomial correlation (Eck et al. 2014) with orders from 2 to 4:

$$K(\theta) = 1 + \sum_j a_j \frac{\theta^j}{\cos\theta} \qquad \text{Eq. 12}$$

5.5.3 End losses

For certification purposes according to ISO 9806 and in the absence of clearly defined in-situ measurement procedures, the collector tests will be accomplished by the installation of a collector sample in a dedicated test bench (Horta and Osorio 2013):
"When dealing with line- focus concentrators, it is likely that single collector modules (limited in length) are to be transported and tested. Experimentally measured longitudinal IAM results are, thus, strongly affected by end losses effects which will only be present once per line in a final installation."

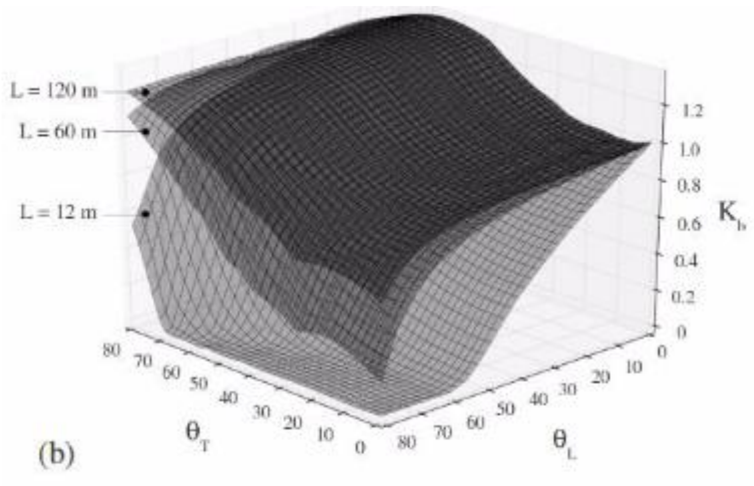

Figure 8: Composed IAM for a 12 m, 60 m and 120 m long LFC (Horta and Osorio 2013)

If a laboratory scale model is tested, the model should include a longitudinal IAM in the form of

$$K(l,\theta) = K_{unit}(\theta)F(l,\theta) \quad \text{Eq. 13}$$

where l is the row length and K_{unit} accounts for all angle dependent effects except the geometrical end losses. Whereas for PTCs there is an analytical solution (Rabl 1976), for LFCs an approximation can be used (Heimsath et al. 2014a).

If, for some collector technology or design, a general analytical expression or a sufficiently good approximation enabling a due length based correction of the IAM doesn't exist, longitudinal (and composed) IAM results for different collector lengths might be produced by simulations with a validated optical model.

In a test report both the IAM without the end losses and a function or a table to include the end losses should be presented.

5.5.4 Ray Tracing simulations to complement experimental results

To understand and compare different ray tracing results, it is important to understand the differences between the alternative ray tracing tools and to determine which are the significant parameters and boundary conditions. To better understand these questions, a comparison of different ray tracing software solutions was performed within the work of IEA Task 49, its results are currently under publication (Osório et al. 2015):
"Ray-Tracing software tools enable a straightforward assessment of optical performance aspects at collector or solar field levels and have been widely used with different proposes, e.g., in the design of solar concentrating collectors, in the evaluation of shading and blocking effects in solar fields or energy flux distributions in central receiver systems. However, up to the present, the use of RT software programs within the certification process of a solar collector is not foreseen in any of the existing standards."

To solve some of the difficulties presented in the application of ISO 9806 *"the use of Ray-tracing analysis could provide important contributions to these issues, complementing the experimental results obtained through thermal testing and allowing the achievement of more thorough testing outputs with lower experimental requirements (Pujol-Nadal 2015).To do so, the first step is to* *understand which optical effects must be considered and included in the physical RT model (Horta and Osorio 2013) and then to distinguish the RT tools which models these physical properties to an acceptable accuracy."*

"Within IEA/SHC Task 49 a comparison between different RT software tools was conducted. Taking as representative technologies for line-focus concentrators the Parabolic Trough Collector (PTC) and the Linear Fresnel Reflector Collector (LFC), each participant was asked to describe their RT software regarding its features and capacities and then to run simulations of two exemplary cases, a PTC and a LFC with predefined conditions: geometry, sun model and material properties."

"Six Task49 participants agreed to take part in the study: University of Évora (UEvora), Institut für Solartechnik (SPF), Universitat de les Illes Balears (UIB), Fraunhofer-Institut für Solare Energiesysteme (ISE), Deutsches Zentrum für Luft- und Raumfahrt (DLR) and Politecnico di Milano (POLIMI) with seven RT tools including open source, commercial and in-house software: Tonatiuh, OptiCAD, OTSun, Raytrace3D, STRAL (with experimental features for PTC RT), SPRAY and SolTrace. The PTC case was modeled by six of the RT tools and the LFC case by four […]" according to Table 11.

Participant	Software	License	Simulation
UEvora	Tonatiuh	Open-source	PTC, LFC
SPF	OptiCAD	Commercial	PTC
UIB	OTSun	In-house	PTC, LFC
ISE	Raytrace3D	In-house	PTC, LFC
DLR	STRAL	In-house*	PTC
DLR	SPRAY	In-house*	PTC
POLIMI	SolTrace	Open-source	LFC

Table 11: Participants software tools and performed simulations (Osório et al. 2015), *copy available on license-fee

The article presents the results of this study and analyzes the differences between the RT tools.

5.5.5 Non-standard iterative procedures to determine the IAM of LFC

Authors: Sven Fahr (FHG-ISE), Annie Hofer (FHG-ISE)

As mentioned in chapter 5.4.2 the standard QDT is not suitable to determine the IAM of regular LFC installations without an additional tracking device. To solve that problem, a combination of ray-tracing results and experimental from a thermal measurement has been successfully used by Fraunhofer ISE to characterize a small-scale LFC with two different methods (see Hofer et al. 2015a). One of them is based on the standard QDT but combined with an iterative process to determine the IAM from starting values based on ray tracing or even less sophisticated geometrical approaches. It works by always setting the IAM of one axis to a fix value and determining the IAM of the other axis together with all other parameters. The results of this IAM determination are then used as a fix values in another round of parameter identification, determining the IAM of the other axis. Figure 9 shows a sketch of this process, which is continued until the changes of all parameters in two subsequent iterations become insignificant *(Hofer et al. 2015a)*.

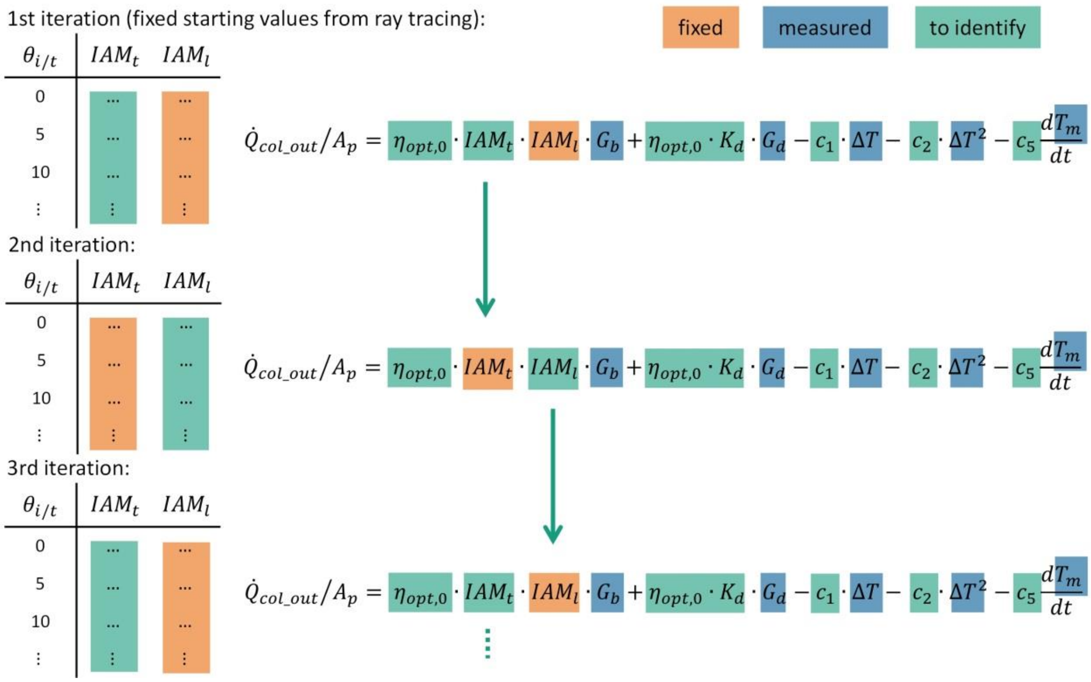

Figure 9: Sketch of the iterative MLR-procedure for the identification of optical and thermal parameters with an adaptive approach for the determination of transversal IAM (IAM_t) and longitudinal IAM (IAM_l) *(Hofer et al. 2015a)*.

The other method is the fully dynamic test method described in chapter 5.4.3. As opposed to the QDT, it uses an optimization algorithm to identify all parameters including the biaxial IAM, but also incorporates ray tracing results as starting values. In a comparative measurement, both methods have shown to deliver equivalent results for the optical parameters and IAM values close to the ray tracing values (Hofer et al. 2015a).

It remains an open questions, whether these approaches should rather be used to just verify the results of ray tracing simulations, which then could be used e.g. for certification purposes, or if their results should be used as final collector parameters. In both cases additional regulations would be necessary, such as:

- Maximum deviation allowed to consider the ray tracing results as verified
- Necessary number of supporting data points
- Minimum range of incidence angles for each axis

5.6 *Output calculator “SCEnOCalc”*

Authors: Sven Fahr (FHG-ISE), Stefan Mehnert (FHG-ISE), Dr. Korbinian Kramer (FHG-ISE)

5.6.1 General aspects

SCEnOCalc is an MS Excel based tool for the calculation of annual energy outputs of solar collectors which was developed within the EU-project QAiST (Quality Assurance in Solar Thermal Heating and Cooling Technologies).
It was designed to give distributers and installers (also end-users) the opportunity to fairly compare different collectors using the efficiency parameters determined by independent test laboratories and a number of different sets of weather data. It computes the annual energy gains for different

temperature levels in a monthly subdivision. It is exclusively focused on the collector output and does not take into account any system configurations or load profiles. It assumes constant fluid temperatures also, thereby no capacity is included.
SCEnOCalc is currently used as the basis for presenting the public available data sheets in the context of the Solar Keymark certification of solar collectors. As it was mainly designed for the use on domestic hot water systems, which mostly use standard flat plate (FPC) and evacuated tubular collectors (ETC) as heat source, it has some shortcomings when it comes to solar process heat collectors, which are mainly concentrating and tracking collectors.
The goal of working group "SCEnOCalc" within Subtask A was to address these shortcomings and to make suggestions how to improve the tool to make it usable for typical process heat collectors such as parabolic troughs (PTC), highly efficient ETC and FPC and Linear Fresnel collectors (LFC).

5.6.2 Deficits of "SCEnOCalc" for the use in solar process heat

Temperature range
The temperature range in the current SCEnOCalc version (v4.06) is limited from 0°C to 100°C which is not sufficient for process heat. The range should be extended, at least to the 185°C for which the current testing standard ISO 9806:2013 provides heat capacity and density fits, even better to higher temperatures (e.g. 210°C), as an extrapolation up to 210°C is supported by the standard.
The "SK-Certificate-evaluation" of SCEnOCalc uses by default mean temperature levels of 25, 50, and 75°C, which are too low for concentrating collectors and too high for non-covered, PVT and solar air heating collectors (SAHC).
To ensure the comparability of the yearly energy yield as calculated by SCEnOCalc and given on page 2 of the SKN-Data-Sheet, it seems helpful to define additional temperature levels. The question which temperature levels shall be used for concentration collectors (and also for other collector technologies such as e.g. non-covered collectors, PVT and SAHC) needs to be addressed in the Solar Keymark Network (SKN).
Note: SCEnOCalc is open source. To calculate for other than the given temperatures is therefore quite easy to do (within the temperature range provided of course).

Selection of collector types
The SKN-Data-Sheet and respectively SCEnOCalc (v4.06) doesn't allow the selection of concentrating collectors although they are eligible for SKM. The only options to choose from are glazed and unglazed flat plate collectors as well as evacuated tubular collectors.
The options PTC and LFC should be added, which will require further changes, e.g. the introduction of θ_i to correctly calculate the influence of the longitudinal IAM for LFCs. Note, that a correct computation of energy yields for concentrating collectors requires a data set that matches the logic of SCEnOCalc calculations and the adequate selection of the tracking mode. In terms of referenced irradiation (DNI vs. G vs. G_b, compare chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**) and the definition of the IAM, the understanding of parametrization in the field of concentrating collectors may differ from that logic. It is necessary to clarify these questions within the SKN and adapt SCEnOCalc if necessary.
The yield calculation should always reference on global irradiance for page 2, but maybe sometimes installers/users have DNI related values available only for input. To mix those is not correct and results in inaccurate ratings!

Tracking modes
There is no possibility to choose a certain tracking mode if "SK Certificate Evaluation" is chosen ("no tracking" is used in any case).

If the user selects "Basic Evaluation" he can select to following modes:
- No tracking

- A. Vertical axis tracking (sets the collector azimuth = sun azimuth and the tilt angle = constant)
- B. Two axis tracking (sets collector azimuth = sun azimuth and collector tilt = zenith angle)
- C. Horizontal NS axis tracking (e.g. usable for PTC or LFC which are orientated in NS direction)
- D. Horizontal EW axis tracking (e.g. usable for PTC or LFC which are orientated in EW direction)

Referenced irradiation

For highly concentrating collectors the referenced irradiation is often DNI. As that is always lower then the global irradiation, the performance value is affected positively. When comparing different collector types for a specific location where also diffuse radiation is available, accounting only for DNI would be a disadvantage for collector types which can use the diffuse fraction as well.
Thus, for SCEnoCalc the reference irradiation for all input parameters has to include beam and diffuse shares, as well as the weather data sets include direct and diffuse radiation values.
Especially low concentrating non-imaging optics used for collectors can for example use a significant ratio of diffuse irradiation. Hence, it is important to represent just any collector with its ability for diffuse and direct radiation acceptance. If in specific cases the diffuse fraction cannot be used this will just “happen” with an extremely low diffuse acceptance angle. For older data sets where this information is not available, the diffuse acceptance can be set to 0 of course.

IAM

The current default uses calculations which are inaccurate for Linear Fresnel Collectors. It does not use θ_i to calculate the longitudinal IAM and it does not provide the possibility to enter IAM-values >0 for incidence angles of 90°, which can occur for concentrating tracking collectors.
Additionally, a separated representation of row end losses should be integrated in the tool. Otherwise it will be not possible to scale results for different row length or the results from the test will be extremely sensible to the row length tested, which is not acceptable. A solution how to separate the row end losses for SCEnOCalc and scaling has been addressed within the recent project “SCF5-Standard_ISE” funded by the Solar Keymark Certification Fund and will be soon be published online[6].

Annotations

- The question “Fluid for testing” within the SKN-Data-Sheet should provide a defined range (Water-Glycol / Water / Air).
- In the future, a growing number of in-situ measurements with thermal oil may ask for the option of user defined fluid parameters.

5.6.3 Further progress

The listed deficits are the minimum changes necessary to make SCEnOCalc usable for solar process heat collectors, especially PTCs and LFCs, other technologies may make additional changes necessary.
The shortcomings will be forwarded to the programmers at SP Technical Research Institute of Sweden but the realization of the improvements is dependent on funding by the SKN.

[6] http://www.estif.org/solarkeymarknew/projects/scf-projects-deliverables

6 In Situ Measurement

Authors: Sven Fahr (FHG-ISE), Annie Hofer (FHG-ISE)

6.1 General aspects

In situ measurements are a most relevant topic in the context of solar process heat collectors for a number of reasons. The most obvious one is that laboratory testing of concentrating collectors, such as LFC and PTC, is very limited in terms of size and at the same time requires high financial effort. Costs arise not only for production, transport and installation of the collector in the lab, but also for the provision of infrastructure and measurement equipment for high temperatures and pressures by the laboratories. Moreover, the argument of higher measurement precision in lab testing is contradicted by various limitations, such as

- Size: testing of short rows of PTC/LFC leads to very dominant row end losses and little temperature gains
- Ambient conditions: Many test labs are located in areas with low DNI, which prolongs the time effort.
- HTF: test labs may not be able to provide hydraulic loops with the HTF, the collector was designed for

Additionally, many process heat collectors may be custom made solutions, optimized in their details to the requirements of the process they are to be integrated in. Consequently, they must be tested in the very configuration to receive significant results, which can either be done at the installation site or requires the production of an additional equivalent test sample.

Of course, in situ characterization raises questions concerning usable sensor equipment, measurement uncertainties, data transfer and integrity as well as system operation, required test sequences and maintenance of sensors and test sample.

In the context of concentrating solar power (CSP), the need for performance evaluations in the field has emerged earlier and is already being addressed, for example by standardization activities in IEC TC 117 (Draft IEC 62862-3-2). Within the Spanish standardization Committee AEN/CTN 206/SC 117 “Thermoelectric solar energy systems” in AENOR, a standard was published in 2015 about the field acceptance test (UNE 206010 2015). Moreover, in the German project StaMeP a guideline was written for field acceptance testing, addressing similar problems as mentioned above (Hofer and Janotte (2015/16).

But the introduction of reliable procedures for performance evaluation in the field is also relevant for non-concentrating collectors, as they may also be custom made and because output control and energy yield based subsidies are becoming major topics. This is why the recently launched German project ZeKon in-situ also addresses these questions and aims to establish a certification process based on in situ measurements applicable to all collector technologies.

6.2 Measurement equipment, uncertainties and calibration

A key question in the context of in situ measurement is the selection of proper measurement devices to assure the necessary precision with respect to the purpose of the measurement campaign (product development, certification, commissioning, output control), technical aspects, ambient conditions and manageable costs. It seems obvious, that the precision of a laboratory test and the requirements in ISO 9806 can hardly always be met in the field without severe cost increase and, thus, undermining the very purpose of in situ testing. It has been shown for some cases that the overall uncertainty of in situ measurements can be within acceptable range, but is very specific to each installation and has to be evaluated individually (Hofer and Janotte (2015/16). Some specifications from the standard may neither be achievable nor be of equal importance for in situ tests than in the laboratory. For example can the relevance of high precision temperature measurement decrease for the extended temperature gain of a very large process heat collector. Within the Best Practice Guideline written in the project StaMeP, these questions have been addressed in detail for collector and field tests in CSP (Hofer and Janotte (2015/16). Conclusions can and need to be transferred to process heat applications, but there is still need for further work. The German project ZeKon in-situ will further investigate these questions with the target to propose regulations applicable to any installation and optimized between necessary precision and financial effort.

6.3 System operation, maintenance and data integrity

Other problems faced when talking about in situ measurements are data integrity and maintenance of the installation and equipment. The institution responsible for testing has to assure that test sample and all measurement devices are well maintained throughout the test procedure, while it will be in most cases impossible to have staff on site at all relevant times. Partly these problems overlap with chapter 6.2, as the need for maintenance is also dependent on the complexity of the measurement equipment. It also must be assured, that neither test equipment nor data can be manipulated in order to influence the test results.
The problem with system operation is that installations in their regular operation mode do usually not produce data sets that are suitable for the evaluation with the standard test methods. Even in the unlikely case, that the operator would allow the test staff to control the installation and run it in concordance with the standard requirements, most of the time the installation will not even provide the necessary technical features. Accordingly, the question of system operation is linked to the evaluation methodology used to characterize the test sample.

6.4 Evaluation / Parameter identification

The requirements for constant process conditions will almost always exclude SST of ISO 9806 to be used for in situ measurement, and most of the times also QDT. If in situ measurement is to become a common testing procedure, a standardized evaluation method is needed, that allows a general characterization of the test sample by interpretation of data from regular operation conditions. A potential solution to this is the Dynamic Testing Method explained in chapter 5.4.3 (Hofer et al. 2015a).

Industry stakeholders have clearly stated their interest and need for in situ testing procedures, not only for certification purposes but also for commissioning and acceptance testing as well as for liability and bankability issues. It is obvious, that there a shortcomings and lacks in terms of commonly agreed testing procedures as well as in terms of administrative questions, which need to be solved.
ZeKon in-situ is a German funded project addressing these questions and aiming to provide a comprehensive solution to make in situ testing eligible for Solar Keymark certification of collectors.

6.5 Field tests

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Discussing field testing, it is important to be transparent and clear on what is the aim to achieve with a specific performed field test. This is strongly depending on the perspective of the different stakeholders. To identify the most suitable technical methods for each situation, they can be sorted according to the following different "field tests" requirements.[7]

Collector Performance Assessment (CPA) from the perspective of a manufacturer shall be as precise as possible and the result is a parameterization from which all future cases can be derived.
This is complicated yet possible in a field but in many cases still performed in laboratories. The information is used for optimization, marketing, and performance prediction for installations, tenders and competition.

The Field Commissioning Test (FCT) in a project shall give performance figures which verify the figures defined beforehand in the specifications of the tender / contract. The period for testing should be short and the costs low. Specific targets have to be achieved in the regular operation mode. The test equipment has to be just precise enough to indicate this fulfillment within a one digit percentage. Here it is very important to understand the risks of uncertainty and very specific ambient performance conditions of the installation, to avoid misinterpretations.

A Field Evaluation Test (FET) may be induced by disputes on the performance of a field installation. This kind of test has to be more precise than a commissioning test and the resolution of information has to be higher, as the results shall show which component may have deficits (e.g. collector, connecting parts, load management). It is normally done by a third party with the relevant accreditation.

Continuous Power Output Test (CPOT) is used, when for example a contracting on delivered energy was placed. The equipment has to calibrated and sealed to prevent unfair manipulations. Often this information is also linked to a continuous presentation of the data on a server platform.

Identifying which information is needed early in the planning process of an installation or a testing issue, is therefore very important.

[7] Spain has defined field test methods for CSP in the standard UNE 206010 (2015)

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