IEC TS 62862-3-3

Edition 1.0 2020-02

TECHNICAL SPECIFICATION

colour inside

Solar thermal electric plants –
Part 3-3: Systems and components – General requirements and test methods for solar receivers

IEC TS 62862-3-3:2020-02(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
67 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC TS 62862-3-3

Edition 1.0 2020-02

TECHNICAL SPECIFICATION

Solar thermal electric plants – Part 3-3: Systems and components – General requirements and test methods for solar receivers

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.160

ISBN 978-2-8322-7784-3

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

SOLAR THERMAL ELECTRIC PLANTS –

Part 3-3: Systems and components – General requirements and test methods for solar receivers

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a Technical Specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62862-3-3, which is a Technical Specification, has been prepared by IEC technical committee 117: Solar thermal electric plants.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
117/104/DTS	117/107/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62862 series, published under the general title *Solar thermal electric plants*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The receiver is one of the most important and most sensitive components of Fresnel and parabolic trough power plants. Large mirrors are aligned to concentrate solar radiation up to 80 times along the focal line of the mirrors onto the specially coated, evacuated receivers. The generated heat is transported to a power generation unit, using a heat transfer fluid, and converted to electricity.

The quality and long-term performance stability of the receiver has a decisive influence on how effectively solar radiation can be converted into heat. For the power plant to achieve maximum efficiency, the receiver has to absorb as much solar radiation as possible and convert it into heat with minimized losses.

The solar receiver (see schematic in Figure 1) mainly consists of:

- a steel absorber tube: heat transfer fluid flows through the stainless-steel absorber tube. A high-quality absorber coating converts the solar radiation into heat and minimizes infrared heat loss at the same time;
- a glass cover tube: the cover is made from borosilicate glass and is coated with an antireflective film to increase solar transmittance;
- evacuated space (annulus) or filled with noble gas between absorber tube and glass cover tube: the vacuum between steel absorber and glass cover is essential to suppress gas heat convection;
- bellows: the bellows are necessary to compensate for different rates of heat expansion of the steel absorber and the glass cover. In contrast to the glass cover, the hot absorber expands considerably when operating.

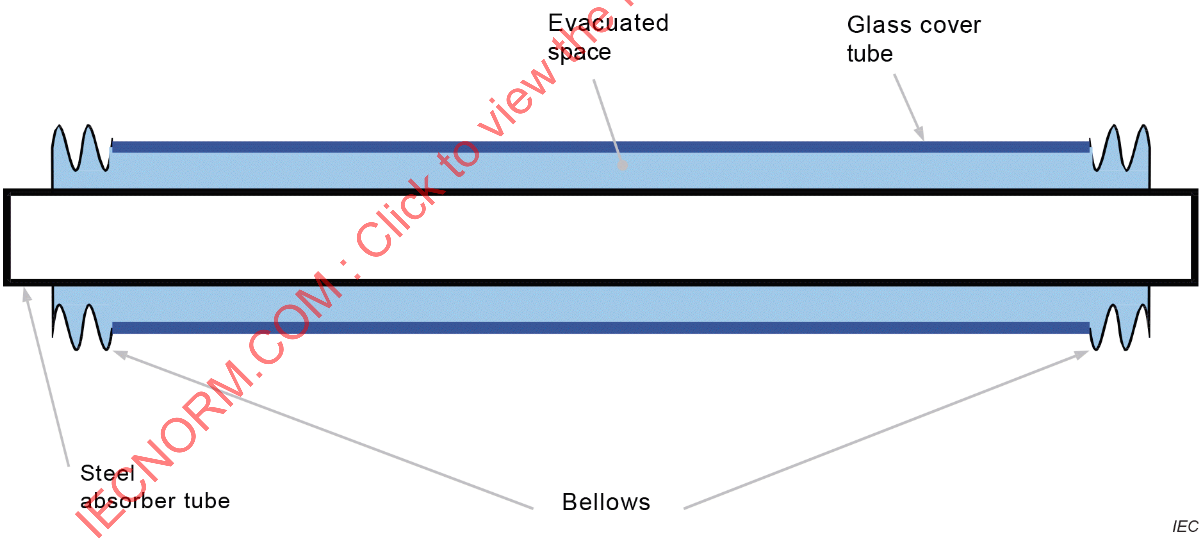


Figure 1 – Solar receiver schematic sketch

SOLAR THERMAL ELECTRIC PLANTS –

Part 3-3: Systems and components –
General requirements and test methods for solar receivers

1 Scope

This document specifies the technical requirements, tests, durability and technical performance parameters of solar thermal receivers for absorbing concentrated solar radiation and transferring the heat to a fluid used in concentrated solar thermal power plants with linear-focus solar collectors. The receivers addressed consist of an absorber tube and an insulating glass envelope tube.

NOTE 1 Most of the test methods included in this document apply to solar receivers used both in solar thermal electric plants with parabolic-trough and Fresnel collectors.

This document includes the definitions of technical properties and characterization of geometry and performance parameters as well as the test methods for optical characterization, heat loss, and durability.

NOTE 2 The experience accumulated so far regarding the different test methods currently available for receiver tubes is not extensive enough to determine which test method is the best; this document describes all the different methods currently available without defining one recommended method.

For the sake of clarity, it is stated here that the thermal loss tests described in this document do not deliver the thermal loss of the receiver tubes when they are installed in commercial solar fields.

Thermal losses obtained by indoor testing on a single receiver are significantly lower than the thermal losses in outdoor, real operating conditions at commercial solar fields. However, the indoor test procedures described in this document are suitable for receiver tube performance comparison.

The thermal losses taken into account for solar field design are obtained by testing complete collectors operating under real solar conditions.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62862-1-1, *Solar thermal electric plants – Part 1-1: Terminology*

ISO 6270-2:2017, *Paints and varnishes – Determination of resistance to humidity – Part 2: Condensation (in-cabinet exposure with heated water reservoir)*

ISO 9806:2017, *Solar energy – Solar thermal collectors – Test methods*

ISO 9488:1999, *Solar energy – Vocabulary*

MIL-E-12397 – *Eraser, Rubber-Pumice (for testing coated optical elements)*

ASTM G173 – 03 – *Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface*

3 Terms, definitions, symbols and units

For the purposes of this document, the terms, definitions, symbols and units contained in ISO 9488 and IEC 62862-1-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Performance test of the receiver

4.1 General

As receivers are one of the most important components in the solar field, they have a big impact on the performance of the entire solar field. In order to be able to best simulate the lifetime performance of the receiver as well as that of the solar field, it is crucial to perform tests that characterize the receiver and its performance.

4.2 Identification and geometry

The receiver usually has a brand name for the product and is also defined by the outer diameter of the stainless-steel tube. Another important identifier/parameter is the length of the receiver, which may vary depending on the trough for which it is designed. Additional parameters such as absorptance, emittance, transmittance, vacuum pressure, stainless-steel material, design temperature and pressure and the Heat Transfer Fluid for which it is designed, can be obtained from the manufacturer. These parameters/characteristics should be noted as part of the report for the receiver being tested.

4.3 Manufacturer's instructions

In addition to the parameters in 4.2, the manufacturer may have additional instructions for the use/preparation of the receiver or parts thereof for testing, for example, the cleaning of samples prior to carrying out optical measurements. These instructions shall be noted as part of the test procedure in case they have an effect on the results.

4.4 Calibration of testing instrumentation

Unless otherwise indicated by the manufacturer of the testing device, all instruments used should be calibrated at least once a year. In the event that a device is used that requires special calibration (i.e. spectrophotometer requiring calibration using a "golden sample"), this should be noted in the report including the date of calibration and the specimen used.

4.5 Heat loss test

4.5.1 General

NOTE In 2016, a round robin test was carried out within the European project STAGE-STE (European Union Seventh Framework Program FP7 (2007-2013) under grant agreement ID 609837) with five different tubes from different manufacturers. From this round robin, the heat loss testing results showed standard deviations in the order of 6 % to 12 % for most temperatures and receivers (see [1][1]).

[1] Numbers in square brackets refer to the Bibliography.

These differences should be considered when comparing results by different laboratories using different methodologies. It is recommended when trying to compare receivers from different manufacturers to test all receivers in the same method at the same institute, to get comparable results.

For the thermal loss test, one of the following methods shall be used (both are described below):

- resistance heating method;
- Joule effect method.

4.5.2 Objective

The purpose of this test is the thermal characterization of a solar receiver tube including determination of the heat loss curve and calculation of thermal emittance (optional) based on test data.

The application of this test is associated with the needs of solar thermal power plant projects using parabolic-trough technology and, by analogy, also Fresnel technology. It is applicable to solar receiver tubes forming part of a parabolic-trough collector or a Fresnel collector.

4.5.3 Receiver tube setup and location

4.5.3.1 General

The way in which the receiver tube is set up on the test bench has a determining influence on the heat loss test results, so it is therefore recommended that the test bench is set up as described in the following subclauses of 4.5.3. The tests shall be performed indoors to minimize any possible environmental influence on the test samples. In addition, the space around the receiver, equal to at least 50 cm on all sides, should be free from big obstacles to avoid limiting natural air circulation.

In the event that the test is carried out under vacuum conditions, the surroundings are not important as air circulation is negligible.

The general principle of measurement is based on the conversion of electricity into heat under stationary conditions. Under these conditions, the heat loss is equivalent to the power necessary to maintain the receiver at a constant temperature. Determination of the power required at different temperatures leads to the heat loss curve characteristic of the receiver test sample.

There are different methods for heating the receiver. For example, by Joule effect, by electrical heated elements or by IR resistance attached to a copper tube inserted inside the absorber tube (see example in [2]).

4.5.3.2 Receiver tube setup and initial inspection

The receiver tube to be tested shall be placed horizontally in the test support frame holders.

The absorber tube shall be visually inspected, and any damage or modification observed shall be recorded in the test report.

4.5.3.3 Temperature measurements

The receiver tube temperature shall be measured with temperature sensors touching the absorber from the inside in at least six positions along it, arranged symmetrically from the centre, with a gap of no more than 1 m between sensors. Additional sensors shall be located near the ends of the tube and be in contact with the tube, in order to control gradients towards the ends. Three sensors are recommended for measuring the glass surface temperature.

The ambient temperature sensor shall be placed not more than 2 m from the sample, in a location where it is not affected by hot spots or air currents. The positions of the sensors shall be recorded in the report.

The temperature sensors shall be calibrated according to the temperature range to be tested.

The expanded uncertainties of the average temperatures of each sensor shall be less than:

- ±2 °C for the absorber tube;
- ±2 °C for the glass envelope tube;
- ±1 °C for ambient or surrounding air.

Uncertainty calculations are determined in accordance with ISO 9806:2017, Annex D.

The contact shall be suitable to ensure correct measurement. Correction methods for compensating the influence temperature gradients near the sensors might be applicable.

Pressing temperature sensors on the absorber or glass often leads to inadequate measurements as temperature sensors are influenced by air temperature and radiation temperature in the annulus and heat conduction along the thermocouple wires. Reference measurements can be used to ensure the validity of the measurement setup or to correct the measurements, see Annex B. The temperature corrections, if done, shall be noted in the test report.

4.5.3.4 Power measurements

The measurement equipment for electric heating power shall have an accuracy of at least 3 % of the actual reading.

4.5.3.5 Data acquisition frequency

Power sensors used in the test shall be calibrated. Data recording frequency shall be no less than 1 recording per 20 s and the minimum number of records shall ensure the statistical representativeness of the test.

4.5.4 Inspection

When the test has finished, the receiver tube shall be inspected and note taken of any change observed. Changes observed shall be recorded in the test report; photographs can be added.

4.5.5 Test methodology – Resistance heating method

4.5.5.1 Measurements

At least the following data shall be measured.

Before the test:

- the length of the metal receiver absorber tube measured at ambient temperature using a measuring instrument (e.g. measuring tape) with an uncertainty of 1 mm. The instrument should be inserted into the tube and measured from one end to the other;
- diameter (inner and outer) of the absorber tube measured at ambient temperature using a caliper with an accuracy of at least 1/10 mm;
- position of temperature sensors using a measuring instrument (e.g. measuring tape) with an uncertainty of at least 1 mm, with reference to a specific end/position on the absorber tube.

During the test:

- temperatures of the absorber tube;
- temperatures of the glass envelope tube (optional);
- temperature of the surrounding air;
- electrical power supplied by the resistance heaters or any other element used.

4.5.5.2 Procedure and test time

The measurement is performed at a steady state of stable absorber temperature and heating power. Therefore, the following arithmetic means of evaluation of the measured quantities over a longer evaluation period, which will also be called measurement point, are used.

Minimum evaluation periods are given in Table 1.

Table 1 – Evaluation periods

Absorber tube temperature in °C	Minimum evaluation period in min
100 to 200	240
200 to 300	120
300 to 400	60
400 to 500	30
> 500	15

Table 2 shows the criteria for stability and homogeneity that shall be met for the duration of the evaluation period.

Table 2 – Stability requirements

Parameter to be monitored	Stability requirement
Absorber tube temperatures	±0,5 °C
Absorber tube temperature homogeneity S_{TH}	< 0,04 $T_{\mathrm{abs,mean,°C}}$
Heat loss (Equation (2))	±1 %
Ambient temperature	20 °C ± 10 °C

Criteria in Table 2 refer to simple moving means (without weights) over 1 min for the quantities of interest. The criterion for absorber tube temperatures refers to the temporal stability for each temperature sensor.

Absorber tube temperature homogeneity S_{TH} (t) at time, t, is defined as the difference of the highest and smallest measured temperature at t divided by the mean temperature:

$$S_{\mathrm{TH}} = \frac{T_{\mathrm{abs,max}} - T_{\mathrm{abs,min}}}{T_{\mathrm{abs,mean}}} \tag{1}$$

The maximum difference measured during one measurement between the different absorber temperatures along the tube is important as it may indicate the uniformity of the coating.

The value of uniformity of S_{TH} should be mentioned in the report. In addition, if during the measurement it was found that S_{TH} > 2 % a warning should be mentioned in the report.

- Method to achieve steady state:

PI or PID controllers can be used to control electric power input to reach target temperature and a steady state. Steady state is achieved when heater set points do not change and the centre-of-glass and absorber temperatures vary by less than 0,5 °C for a period of at least 15 min.

- This criterion of uniformity shall be followed throughout the steady-state period.

Once the desired absorber tube test temperature is reached and the adiabaticity of the process at the ends of the tube is verified, measurements for steady-state periods shall be performed. A measurement steady-state period shall have a duration of 15 min during which the stability conditions listed in Table 2 shall be verified. Before each steady-state period, a 30-min period shall verify the same stability conditions listed in Table 2.

4.5.5.3 Heat loss (HL) calculations

Calculations shall be done using measurement point means.

The uncertainty of measurement shall be calculated in accordance with ISO 9806:2017, Annex D.

The coefficient of loss in a receiver tube is defined as:

$$HL = \frac{\sum_i Pow_i + HL_{\text{ends}}}{L_{\text{HCE}(25\,°\text{C})}} \tag{2}$$

where

HL is the heat loss of the tube [W/m];

Pow_i is the electrical power consumed by heating element i [W];

HL_{ends} is the heat loss at the tube ends [W].

Example of a test bench with a copper tube as heater type:

For this type of test bench, only the ends are insulated; the heat loss of the ends should be calculated, for example, in the following way:

$$HL_{\text{ends}} = \frac{kA}{\Delta x}\left(T_1 - T_2\right) + \frac{kA}{\Delta x}\left(T_N - T_{N-1}\right) \tag{3}$$

where

$T_{1/2/N/N\text{-}1}$ indicates the temperatures measured by sensors at the ends [°C] assuming N sensors. In the case of a test bench based on electrical heating elements, the sensors at the ends of the copper tube would be taken;

k is the coefficient of conductivity of copper [W/m °C];

A is the surface area of copper tube (heater) [m^2];

Δx is the distance between sensors at ends [m];

$L_{\text{HCE}(25\,°\text{C})}$ is the length of receiver tube at ambient temperature (25 °C ± 10 °C) [m]. The length of the receiver tube aperture shall be measured.

The mean temperature of the absorber is calculated by weighting the distance that each sensor covers along the absorber tube:

$$T_{\text{abs}} = \frac{\sum_i T_{\text{abs}_i} p_i}{\sum_i p_i} \ [°\text{C}] \tag{4}$$

where

T_{abs_i} is the absorber tube temperature measured by sensor i [°C];

p_i is the weight applied [-].

The mean temperature of the glass envelope tube is:

$$T_{\text{gl,o}} = \frac{\sum_i T_{\text{gl,o}_i} p_i}{\sum_i p_i} \tag{5}$$

where

$T_{\text{gl,o}_i}$ is the outer temperature of the glass envelope tube measured by sensor i [°C];

p_i is the weight applied [-].

Weights used to find the absorber and glass temperatures are calculated by the following equations:

$$P_i = \frac{A_i}{A_{\text{abs}}} \tag{6}$$

where

$$A_{\text{abs}} = d_{\text{abs}} \times l_{\text{abs}}, RT \tag{7}$$

is the area of the absorber at room temperature and A_i is that fraction of the absorber area for which the temperature sensor i is the closest sensor.

Optional: In general the result of a measurement point is a pair of heat loss HL and mean absorber temperatures, T_{abs}. Both have associated uncertainties $u(HL)$ and $u(T_{\text{abs}})$. Interpreting heat loss HL as a function of temperature T_{abs} it is beneficial to have only HL associated with uncertainty. Uncertainty of temperature $u(T_{\text{abs}})$ and uncertainty of heat loss $u(HL)$ can be merged to form a combined uncertainty of heat loss $u_{\text{c}}(HL)$ by:

$$u_{\text{c}}^2(HL) = u^2(HL) + \left(\frac{\partial HL(T_{\text{abs}})}{\partial T_{\text{abs}}}\right)^2 \times u^2(T_{\text{abs}}) \tag{8}$$

The partial derivative $\partial HL(T_{\text{abs}}) / \partial T_{\text{abs}}$ can be determined from the interpolation polynomials, for example.

4.5.5.4 Thermal emittance calculation (optional)

Emittance can only be calculated if the annulus between the steel tube and glass cover is evacuated (not filled with noble gas).

Emittance is calculated (optional) in several steps starting with the test results.

First the outside absorber tube temperature is calculated:

$$T_{\text{abs},o} = T_{\text{abs},i} - \frac{HL \ln\left(\frac{r_{\text{abs},o}}{r_{\text{abs},i}}\right)}{2\pi k_{\text{abs}}} \tag{9}$$

where

HL is heat loss measured during the test at a given T_{abs} [W/m];

$r_{\text{abs,o}}$ is the outer radius of the absorber tube [m];

$r_{\text{abs,I}}$ is the inner radius of the absorber tube [m];

k_{abs} is the thermal conductivity of the absorber [m/°C] – to be received from manufacturer;

$T_{\text{abs,i}}$ is the inner absorber temperature [°C] (also called T_{abs}).

NOTE The radii, $r_{\text{abs},i}$ and $r_{\text{abs},o}$ are supplied by the manufacturer, as are those for the glass tube in Formula (10).

Second, the temperature inside the glass envelope tube is calculated:

$$T_{\text{gl},i} = T_{\text{gl},o} + \frac{HL \ln\left(\frac{r_{\text{gl},o}}{r_{\text{gl},i}}\right)}{2\pi k_{\text{gl}}} \tag{10}$$

where

$r_{\text{gl},o}$ is the outer radius of the glass envelope tube [m];

$r_{\text{gl},i}$ is the inner radius of the glass envelope tube [m];

k_{gl} is the thermal conductivity of glass [m/°C] – to be received from manufacturer;

$T_{\text{gl},o}$ is the outer temperature of the glass envelope tube [°C].

Finally, the absorber tube emittance is calculated using the Forristal equation (Equation (11)):

$$\varepsilon_{\text{abs}} = \frac{HL}{2\pi r_{\text{abs},o}\sigma\left(T_{\text{abs},o(K)}{}^4 - T_{\text{gl},i(K)}{}^4\right) - HL\frac{1-\varepsilon_{\text{gl}}}{\varepsilon_{\text{gl}}}\left(\frac{r_{\text{abs},o}}{r_{\text{gl},i}}\right)} \tag{11}$$

where

ε_{gl} glass emittance [-] (use value provided by manufacturer; if none provided, use 0,89);

σ Stefan-Boltzman constant [].

4.5.6 Test methodology – Joule effect method

4.5.6.1 Testing apparatus schematic layout

The Joule effect heating method consists in using the steel tube itself as a heater in order to provide the required power to bring the receiver to a certain temperature.

Its schematic layout is shown in Figure 2. The receiver ends are mechanically and electrically connected with two pieces of well insulated steel tube (220 mm minimum length) with the same outer diameter and thickness as the tube under test.

The ends of these tube extensions are connected to a current (preferred) or voltage generator. During the test the voltage differences in some critical points as well as the current flowing into the circuit are measured in order to determine the exact amount of power transferred to the tube in the different sections.

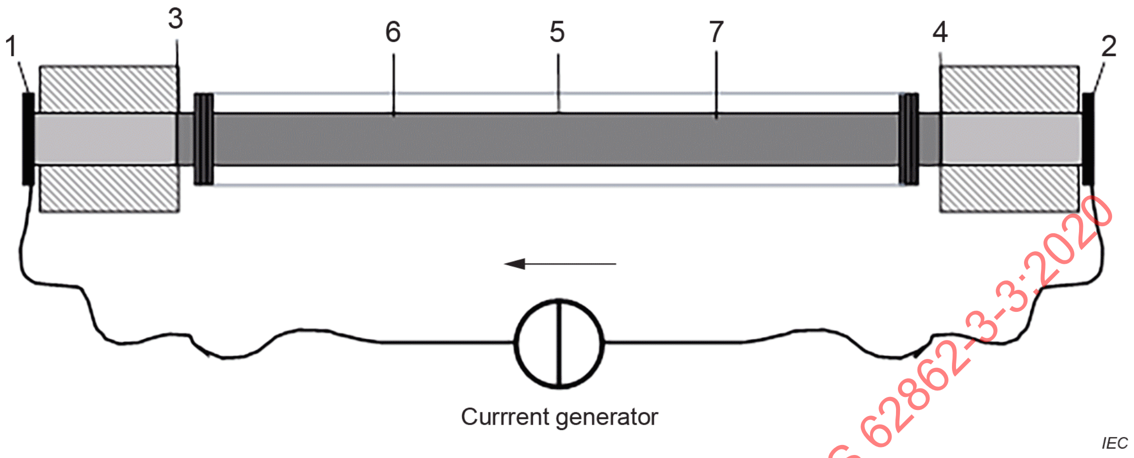


Figure 2 – Resistance heating method schematic sketch

4.5.6.2 Effective voltage measurements

The effective voltage on the receiver tube shall be measured with suitable probes touching the absorber tube from the inside, where the steel tube is not accessible, and/or from the outside in the other positions shown in Figure 2.

The effective voltage difference should at a minimum be measured in the following positions using the low-voltage reference at one end of the testing equipment set-up: at point 1 in Figure 2; close to the other current connection clamp at other end of the set-up (point 2); as close as possible to both the receiver tube ends (points 3 and 4); at least in 3 other positions along it (points 5 to 7), arranged symmetrically from the centre to evaluate the central *HL* value.

The expanded uncertainties of each voltage sensor shall be less than ±1 mV.

Uncertainty calculations are determined in accordance with ISO 9806:2017, Annex D.

4.5.6.3 Current measurements

The current flowing into the receiver tube shall be measured with a suitable instrument to be connected in series in the electric loop.

The expanded uncertainties of the current sensor shall be less than ±0,1 A.

Uncertainty calculations are determined in accordance with ISO 9806:2017, Annex D.

4.5.6.4 Power measurements

The equipment for measuring electric heating power (based on calculations from the voltage and current measurements) shall have an accuracy of 2 % to 3 % of the actual reading.

4.5.6.5 Data acquisition frequency

Power sensors used in the test shall be calibrated. Data recording frequency shall be no less than 1 recording per 20 s and the minimum number of records shall ensure the statistical representativeness of the test.

4.5.6.6 Measurements

At least the following data shall be measured.

Before the test:

- the length of the metal receiver absorber tube measured at ambient temperature using a measuring instrument (e.g. measuring tape) with an uncertainty of 1 mm. The instrument should be inserted into the tube and measured from one end to the other;
- diameter (inner and outer) of the absorber tube, measured at ambient temperature using a caliper with an accuracy of at least 1/10 mm;
- position of temperature sensors using a measuring instrument (e.g. measuring tape) with an uncertainty of at least 1 mm, with reference to a specific end or position on the absorber tube;
- position of the voltage sensors using a measuring instrument (e.g. measuring tape) have an uncertainty of at least 1 mm with reference to a specific end or position on the absorber tube.

During the test:

- temperatures of the absorber tube;
- temperatures of the glass envelope tube (optional);
- temperature of the surrounding air;
- voltage differences across the different measuring points;
- current flowing in the circuit;
- electrical power supplied by the resistance heaters or any other element used.

4.5.6.7 Test conditions

The ambient temperature sensor shall be placed not more than 2 m from the sample, in a position where it is not affected by hot spots or air currents.

4.5.6.8 Test bench

Figure 3 shows the test bench for performing the measurements.

IEC

Figure 3 – Test bench for heat loss measurements of solar receiver tubes

4.5.6.9 Setup of test bench

At the ends of the absorber tube in Figure 3, two simple heaters are mechanically and electrically connected (by bolts or other suitable system); these heaters are comprised of two steel tubes of the same diameter as the absorber tube and length not less than 220 mm.

The external surface of these heaters is insulated by glass wool made for high temperatures (with thickness of about 25 mm), covered by a sheet of aluminium.

The end sections of the heaters are thermally insulated by glass wool inserted into the tube for not less than 80 mm.

The aim of these end heaters is to reduce the axial temperature gradient, to minimize the axial heat loss of the absorber tube. The electric clamps are connected by bolts or other suitable systems to the free ends of the heaters.

Figure 4 shows a typical axial position of the temperature sensors used for measuring the axial distribution of the steel and glass tubes' temperature.

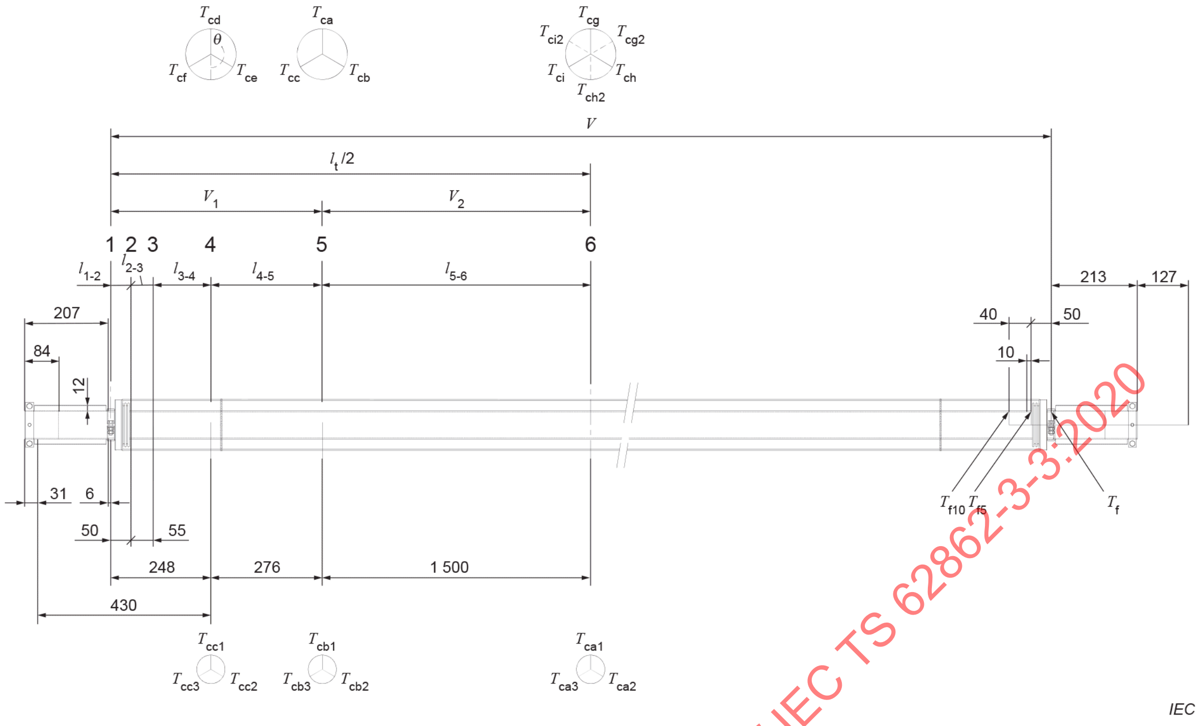


Figure 4 – Position of thermocouples and sections of voltage measurement

4.5.6.10 Test conditions

The ambient temperature sensor shall be placed not more than 2 m from the sample, in a location where it is not affected by hot spots or air currents.

4.5.6.11 Procedure and test time (as per the resistance heating method)

The measurement is performed at steady state of stable absorber temperature and heating power. Therefore, the following arithmetic means to evaluate the measured quantities (also called "measurement points") over a longer period are used.

Minimum evaluation periods are given in Table 3.

Table 3 – Evaluation periods

Absorber tube temperature in °C	Minimum evaluation period in min
100 to 200	240
200 to 300	120
300 to 400	60
400 to 500	30
> 500	15

Table 4 shows the criteria for stability and homogeneity that shall be met for the duration of the evaluation period.

Table 4 – Stability requirements

Parameter to be monitored	Stability requirement
Absorber tube temperatures	±0,5 °C
Absorber tube temperature homogeneity S_{TH}	< 0,04 $T_{abs,mean,°C}$
Heat loss (Equation (2))	±1 %
Ambient temperature	20 °C ± 10 °C

Criteria in Table 4 refer to simple moving means (without weights) over 1 min for the quantities of interest. The criterion for absorber tube temperatures refers to the temporal stability for each temperature sensor.

Absorber tube temperature homogeneity S_{TH} (t) at time t is defined as the difference between highest and smallest measured temperature at time t divided by the mean temperature:

$$S_T = \frac{T_{abs,max} - T_{abs,min}}{T_{abs,mean}} \tag{12}$$

The maximum difference measured during one measurement between the different absorber temperatures along the tube is important as it may indicate the uniformity of the coating.

The value of uniformity of S_T should be mentioned in the report. In addition, if, during the measurement, it was found that S_T > 2 %, a warning should be mentioned in the report.

PI or PID controllers can be used to control electric power input to reach target temperature and a steady state. Steady state is achieved when heater set points do not change and the centre-of-glass and absorber temperatures vary by less than 0,5 °C for a period of at least 15 min.

This criterion of uniformity shall be followed throughout the steady-state period.

Once the desired absorber tube test temperature is reached and the adiabaticity of the process at the ends of the tube is verified, measurements for steady-state periods shall be performed. A measurement of the steady-state period shall have a duration of 15 min during which the stability conditions listed in Table 4 shall be verified. Before each steady-state period, the same stability conditions listed in Table 4 shall be verified for a 30 min period.

4.5.6.12 Evaluation of heat loss (HL)

Evaluation of heat loss in the central part of the tube:

In this condition the central heat loss per unit length of the receiver at the steady state can be evaluated as follows:

$$HL(T_{5\text{ to }6}) = \frac{\Delta V_{5\text{ to }6}}{L_{5\text{ to }6}} I \cos \varphi \tag{13}$$

where

$HL(T_{5\text{ to }6})$ is the heat loss in the central part [W/m];

$(T_{5\text{ to }6})$ is the mean temperature of the steel tube in the section 5 to 6 as per Figure 4 [°C];

$\Delta V_{5\text{ to }6}$ is the effective difference voltage measured between sections 5 and 6 [V];

$L_{5\text{ to }6}$ is the length of the 5 to 6 section of the tube at 25 °C;

I is the effective electric current flowing in the tube;

φ is the phase angle between voltage and electric current [rad].

Evaluation of heat loss in the whole tube:

Overall heat loss per unit length of the receiver at the steady state can be evaluated as follows:

$$HL(T) = \frac{\Delta V_{3\text{ to }4}}{L} I \cos\varphi \tag{14}$$

where

$HL(T)$ is the heat loss in the central part [W/m];

T is the mean temperature of the steel tube [°C];

L is the length of the tube at 25 °C;

$\Delta V_{3\text{ to }4}$ is the effective difference voltage measured between sections 3 and 4 [V];

I is the effective electric current flowing in the tube;

φ is the phase angle between voltage and electric current [rad].

4.5.7 Thermal emittance (optional)

Emittance can only be calculated if the annulus between the steel tube and glass cover is evacuated (not filled with noble gas).

Emittance is calculated (optional) in several steps starting with the test results:

First the outside absorber tube temperature is calculated:

$$T_{\text{abs},o} = T_{\text{abs},i} - \frac{HL \ln\left(\frac{r_{\text{abs},o}}{r_{\text{abs},i}}\right)}{2\pi k_{\text{abs}}} \tag{15}$$

where

HL is heat loss measured during the test at a given T_{abs} [W/m];

$r_{\text{abs},o}$ is the outer radius of the absorber tube [m];

$r_{\text{abs},i}$ is the inner radius of the absorber tube [m];

K_{abs} is the thermal conductivity of the absorber [m/°C] – to be received from manufacturer;

$T_{\text{abs},i}$ is the inner absorber temperature [°C] (also called T_{abs}).

NOTE The radii $r_{\text{abs},i}$ and $r_{\text{abs},o}$ are supplied by the manufacturer, as are those for the glass tube in Formula (16).

Second, the temperature inside the glass envelope tube is calculated:

$$T_{\text{gl},i} = T_{\text{gl},o} + \frac{HL \ln\left(\frac{r_{\text{gl},o}}{r_{\text{gl},i}}\right)}{2\pi k_{\text{gl}}} \tag{16}$$

where

$r_{gl,o}$ is the outer radius of the glass envelope tube [m];

$r_{gl,i}$ is the inner radius of the glass envelope tube [m];

k_{gl} is the thermal conductivity of glass [m/°C] – to be received from manufacturer;

$T_{gl,o}$ is the outer temperature of the glass envelope tube [°C].

Finally, the absorber tube emittance is calculated using the Forristal equation (Equation 17):

$$\varepsilon_{abs} = \frac{HL}{2\pi r_{abs,o}\sigma\left(T_{abs,o(K)}{}^{4} - T_{gl,i(K)}{}^{4}\right) - HL\frac{1-\varepsilon_{gl}}{\varepsilon_{gl}}\left(\frac{r_{abs,o}}{r_{gl,i}}\right)} \tag{17}$$

where

ε_{gl} is the glass emittance [-] (use value provided by manufacturer; if none provided, use 0,89);

σ is the Stefan-Boltzman constant [].

4.5.8 Heat loss and emittance curve models

4.5.8.1 General

The parameters of heat loss HL and emittance ε are calculated by statistical fit of curves using the least squares method to find the curves described in 4.5.8.2 and 4.5.8.4.

4.5.8.2 Heat loss curves

The test results lead to the heat loss at each receiver tube operating temperature (T_{abs}). The heat loss curve is represented in Equation (18):

$$HL = a_1 T_{abs} + a_2\, T_{abs}{}^{4} \tag{18}$$

Coefficient a_1 [W/(m·°C)] and a_2 [W/(m·°C$_4$)] are fit parameters.

The choice of the type of fit of the equation depending on the temperature and the temperature to a power of four is due to the heat transmission mechanism of the tube itself. The first term in Equation (18) refers to loss from convection, while the second term refers to loss from radiation to ambient.

NOTE The curve is an empirical fitting curve.

The test report shall contain a plot of the experimental points and heat loss in the receiver tube according to Equation (12) for T_{abs} in the range measured.

An example of a heat loss curve is shown in Figure 5.

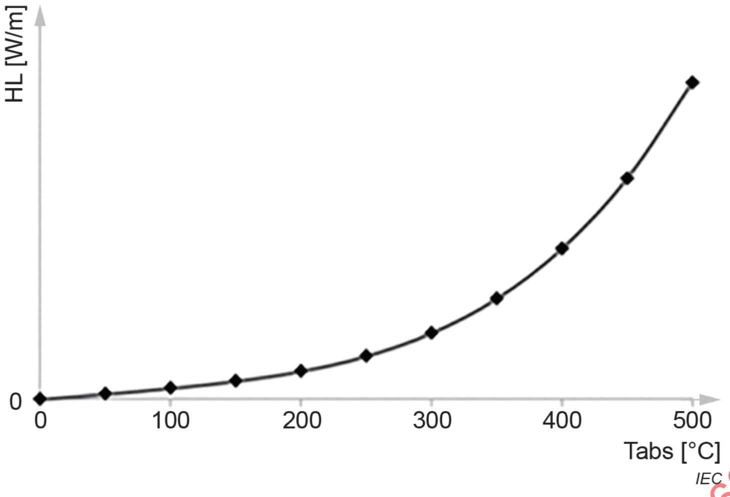


Figure 5 – Example heat loss curve

4.5.8.3 Heat loss interpolation

Heat loss results $HL(T_{abs})$ can be interpolated to temperatures of interest. Two methods can be used for interpolation – the method chosen should be mentioned in the report:

- Interpolation by heat loss curve: Using Equation (12), heat loss can be calculated at temperatures of interest. However, Equation (12) has small systematic deviations to measured curves. Hence, in the case of interpolation for oil receivers, the parameters of Equation (12) shall be calculated with heat loss measurement data at 250 °C, 300 °C, 350 °C, and 400 °C (each ±10 °C), and interpolation shall be to 250 °C, 300 °C, 350 °C, or 400 °C. In the case of interpolation for salt receivers, the parameters of Equation (12) shall be calculated with heat loss measurement data at 250 °C, 300 °C, 400 °C, 500 °C, and 550 °C (each ±10 °C), and interpolation shall be to 250 °C, 300 °C, 400 °C, 500 °C, or 550 °C.
- Interpolation by spline: Interpolation by spline shall be performed with cubic splines with not-a-knot condition. The measurement results of pairs of T_{abs} and HL are called knots in the following. Cubic splines are piece-wise defined third order polynomials. Each polynomial is defined between two neighbouring knots. Hence, with N knots there are N-1 polynomials. The set of polynomials is required to contain the knots, to be continuous at the knots in the first derivative and to be continuous at the knots in second derivative. With these requirements, there are two degrees of freedom left for the polynomials. Hence, a popular choice for the two remaining degrees of freedom is to require the third derivative to be continuous at the second knot and at the penultimate knot. This additional requirement is also called not-a-knot condition. Interpolation shall not exceed 15 °C from an actual measurement. Extrapolation shall not exceed 5 °C from an actual measurement.

4.5.8.4 Emittance curve (optional)

The test results lead to emittance at the various temperatures T_{abs}. Emittance is represented by Equation (19):

$$\varepsilon_{abs} = b_1 + b_2\ T_{abs}^{\ 2} \tag{19}$$

where

coefficient b_1 (W/(m·°C))	is the coefficient of emittance dependence on absorber temperature T_{abs};
coefficient b_2 (W/(m·°C^2))	is the coefficient of emittance dependence on the absorber temperature squared $T_{abs}^{\ 2}$.

The test report shall contain a plot of the experimental points and absorber tube emittance according to Equation (13) for T_{abs}.

The formula in Equation (19) should not be used below the minimal measuring temperature. Results of the inspection and of the electrical power consumption, ambient temperature, and the temperature of the absorber tube and glass envelope during the test shall be recorded. Any anomalies shall be shown in the report, to which a photograph or diagram of the sample tested in its final condition shall be attached.

4.5.9 Test report

See Annex A.

4.6 Optical characterization test

4.6.1 General

The purpose of this test is the optical characterization of a solar receiver tube.

The application of this test is associated with the needs of solar thermal power plant projects using parabolic-trough technology, and, by analogy, also Fresnel technology. It is applicable to solar receiver tubes in parabolic-trough or Fresnel collectors.

For the optical characterization test, one of the following methods shall be used:

- method of measuring τ and α for small samples (can be done on pre-prepared slide samples or by destructive test on tubes) (see 4.6.2).
- non-destructive method to measure τ and α for a complete tube (see 4.6.3).
- non-destructive method $\tau \times \alpha$ for a complete tube, with elliptical solar simulator (see 4.6.5) or outdoor test bench (see 4.6.4).

The tubes shall be tested at a minimum in accordance with one of the optical methods.

It is noted that the methods described in 4.6.2 and 4.6.3 in practice yield results which have much less uncertainty than the tests given in 4.6.4 and 4.6.5 because of the test methodology and the number of sources of error involved in the process. A method for optical characterization of solar glass cover and solar absorbers using spectrophotometers is given below.

4.6.2 Objective

4.6.2.1 General

The purpose of this test is to cover the measurement of spectral hemispherical reflectance and transmittance of materials used in solar thermal technologies for calculating solar absorptance and transmittance. This method uses spectrophotometers equipped with integrating spheres. The method of computing solar weighted properties from the measured spectral values is also specified.

The scope of application of the test is the materials used as absorbers in solar thermal technologies (line focus solar collectors) and the glass material, with or without antireflective coating, used as covers in the same technologies.

4.6.2.2 General method

In this method, measurements of spectral near-normal hemispherical transmittance (or reflectance) are made over the spectral range from 300 nm to 2 500 nm with an integrating sphere spectrophotometer. The solar transmittance or absorptance is obtained by calculating a weighted average with a standard solar spectral irradiance according to the definitions contained in IEC 62862-1-1.

Solar absorptance and transmittance are key parameters to evaluate the optical efficiency of solar thermal electricity plants. This test method is designed to provide reproducible data appropriate for comparison of results among laboratories or at different times by the same laboratory and for comparison of data obtained on different materials.

For applications using direct solar radiation, the AM (air mass) 1,5 D spectrum is used to find the direct solar reflectance. The ASTM G173-03 AM 1,5 solar radiation spectrum shall be used to calculate the solar reflectance.

4.6.2.3 Instrumentation

4.6.2.3.1 General

The type of spectrophotometer shall be fully detailed in the report, as well as the uncertainty of the device used, and the specimen used for calibration and/or reference sample.

4.6.2.3.2 Spectrophotometer

A spectrophotometer with an integrating sphere attachment capable of measuring the spectral characteristics of the test specimen or material over the solar spectral region from 300 nm to 2 500 nm is required. The design shall be such that the specimen may be placed in direct contact with the sphere aperture for both transmission and reflection, so that the incident radiation is near (less than 15°) normal to the plane of the specimen. In this way, the specular component of the reflected energy is not lost through an aperture. Ambient light shall be prevented from entering the sphere.

The interior of the integrating sphere shall be finished with a stable, highly reflecting and diffusing coating. Materials such as polytetrafluoroethylene and $BaSO_4$ satisfy the required properties. The ratio of the port area to the sphere wall plus port area shall be lower than 4 %. This low port fraction ensures good integration of the sample signal before it reaches the sphere's detector. Spheres ≥ 150 mm are preferred.

4.6.2.3.3 Reference samples

In general, both reference and working (comparison) reference samples are required. Reference samples are the primary means for the calibration of instruments and working samples.

For transmitting specimens (glass or antireflective coatings on glass), incident radiation shall be used as the standard relative to which the transmitted light is evaluated. For very high transmitting specimens, a zero-line correction is required. Light traps, diffusing black material or blocking the beam can be used for this purpose.

4.6.2.4 Test specimen and conditions

The test specimens will be cut from a receiver tube. The size of test specimens required depends on the dimensions of the integrating sphere. The specimen shall be large enough to cover the aperture of the sphere. For curved specimens, the part that covers the aperture of the sphere should be essentially plane. In this case, a special holder that allows the perfect adjustment between the curved sample and the aperture of the sphere shall be used.

4.6.2.5 Procedure – Measurement

For all measurements, at least one value each 10 nm shall be recorded in the 300 nm to 2 500 nm range.

Transmittance: Cover the specimen and reference ports at the rear of the sphere with surfaces having the same coating and optical properties as the sphere walls when measuring transmittance. Record the spectral curves without any specimen in place and then with the specimen over the specimen beam entrance port of the sphere.

To calculate the spectral transmittance, Formula (20) is used if the beam passes through only one of the faces of the tube or a semi-circumferential cut section of the tubes:

$$\tau(\lambda) = (S_\lambda - Z_\lambda) / (100_\lambda - Z_\lambda) \tag{20}$$

where

S_λ is the signal recorded with the specimen over the entrance port;

Z_λ is the zero line reading with the specimen beam blocked with an opaque material; and

100_λ is the line recorded with no specimen over the specimen beam entrance port.

Absorptance: For obtaining the absorptance of absorber specimens it is necessary to record the hemispherical reflectance spectrum and then it is obtained subtracting from 1, that is, τ_λ = 0 in the next relationship:

$$\alpha_\lambda + \tau_\lambda + \rho_\lambda = 1 \tag{21}$$

Reflectance measurement: Record the zero line indicated above and the spectral 100 % line by placing the working standard on the sample port. Record the spectral reflectance of specimen by placing the specimen on the sample port. Include the specular component in the reflectance measurement.

Compute the spectral reflectance, $\rho(\lambda)$, for the specimen, at wavelength λ using:

$$\rho(\lambda) = \left[(S_\lambda - Z_\lambda) / (100_\lambda - Z_\lambda)\right]\rho'_\lambda \tag{22}$$

where

S_λ is the recorded specimen reading;

Z_λ is the zero-line reading;

100_λ is the 100 %-line reading; and

ρ'_λ is the calibrated spectral reflectance for the working standard or reference, all at wavelength λ.

4.6.2.6 Test report

The report shall include the following information:

- complete identification of the material tested, from which receiver it was taken, specimen size and thickness, surface contour if any;
- solar transmittance, absorptance, or reflectance, or all three, determined to the nearest 0,001 unit or 0,1 %;
- identification of the instrument used. The manufacturer's name and model number including modifications, accessories, integrating sphere size, are sufficient for a commercial instrument. Other instruments shall be described in detail including estimations of their accuracy;
- complete identification of the standards used in the measurements;

- reference solar spectral irradiance used for computation of the solar optical property.

4.6.3 Method of non-destructive optical characterization (optional)

4.6.3.1 General

NOTE This is a method of normal specular absorptance or transmittance measurement. It is not equivalent to the measurement method described in 4.6.1, which is a method of normal hemispherical absorptance or transmittance.

4.6.3.2 Objective

The objective of this test is to characterize the optical properties of the receiver tube, measuring solar spectrum transmittance of the glass tube and reflectance of the absorber tube in different sections along the receiver tube, while the receiver is fully intact. Usually one device does both tests using one system for transmittance testing and another for absorptance testing (see Figure 6).

The specimen is to be cleaned before testing according to the manufacturer's instructions.

4.6.3.3 Instrumentation – Laboratory devices

Spectral reflectance and spectral transmittance shall be measured for quasi-parallel radiation and quasi-normal incidence with equipment having the following requirements:

- spectral range from 300 nm to 2 500 nm every 10 nm;
- near normal incidence: incidence angle from 6° to 15° to normal;
- minimum acceptance angle 12,5 mrad.

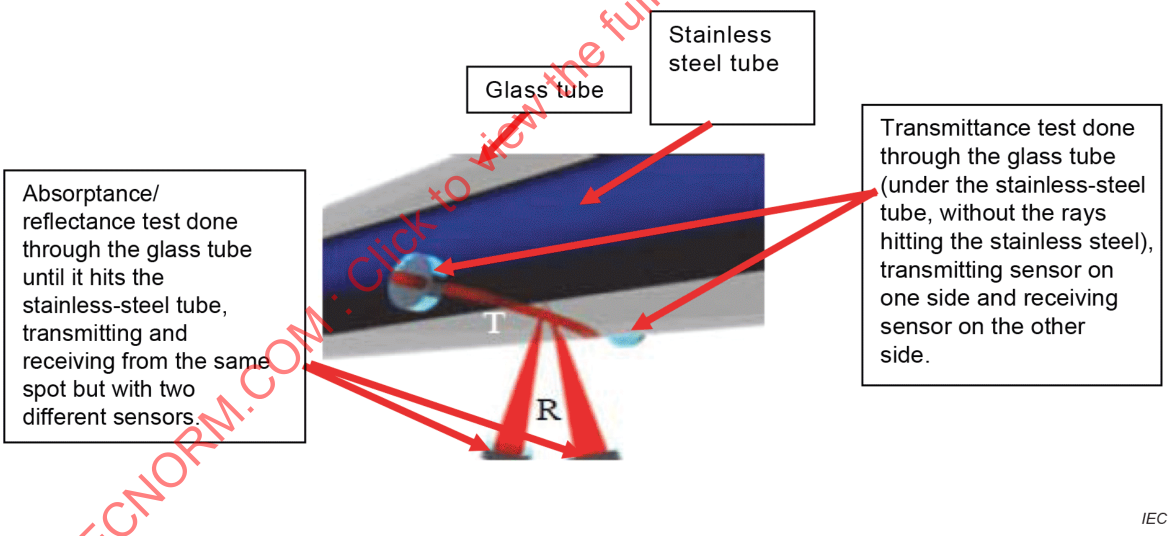


Figure 6 – Measurement principle

4.6.3.4 Test conditions

The maximum variations allowed for the different tested points for the surrounding air temperature are 20 °C ± 10 °C.

The temperature sensor is placed no further than 2 m away from the tube, with a minimum height of 2 m above the ground, avoiding placing the sensor next to heating or cooling sources (e.g., air vents, exterior walls, heat sources).

4.6.3.5 Procedure

Spectral reflectance and spectral transmittance shall be measured along the tube in at least 10 different positions.

4.6.3.6 Test results and report

The following expressions shall be used:

$$\alpha_S = \frac{\sum_{\lambda_1}^{\lambda_2} (1-\rho(\lambda_i)) E(\lambda_i) \Delta\lambda_i}{\sum_{\lambda_1}^{\lambda_2} E(\lambda_i) \Delta\lambda_i} \qquad \tau_S = \frac{\sum_{\lambda_1}^{\lambda_2} \tau(\lambda_i) E(\lambda_i) \Delta\lambda_i}{\sum_{\lambda_1}^{\lambda_2} E(\lambda_i) \Delta\lambda_i} \tag{23}$$

where

$\rho(\lambda_i)$ is the measured spectral reflectance [-];

$\tau(\lambda_i)$ is the measured spectral transmittance [-];

λ_i is the wavelengths measured [nm];

$\Delta\lambda_i$ is the interval of the respective wavelengths [nm];

$E\lambda i$ is the spectral distribution of the direct solar irradiance AM 1,5 D (i.e. ISO 9845-1 or ASTM G173 can be used). $S_{\lambda i}$ shall be found by interpolation for the specific wavelengths measured and added up appropriately over the respective wavelength interval.

At least the following characteristics and testing conditions shall appear in the report:

- ambient temperature,
- wavelengths measured,
- equipment used,
- angle of incidence to normal,
- angle of acceptance,
- solar absorptance and solar transmittance,
- solar spectrum used for the integral,
- measurement accuracy,
- size of measurement spot,
- how the specimen was cleaned.

4.6.4 Optical efficiency test – A transient method (optional)

4.6.4.1 Objective

The purpose of the receiver's optical efficiency test is to determine the optical absorption of solar radiation by a tubular receiver by evaluating the slope of the temperature of the fluid circulating inside the tube versus the time during an interval of steady-state solar radiation when heat losses are null. The optical efficiency is calculated from a simple energy balance. The test is performed in an outdoor test bench under natural solar radiation, i.e. using the actual solar spectrum. This test is non-destructive and provides, in one measurement, the receiver optical efficiency, i.e. the combined value of the absorptance and transmittance of the receiver tube.

4.6.4.2 General

The optical efficiency test measures the slope of the fluid temperature versus the time during an interval of steady-state solar radiation, near the point at which the average glass temperature is close to the average absorber temperature, and when heat losses are null, i.e.

the fluid temperature is similar to ambient temperature. Comparative tests are possible with any set of samples of similar geometry. During the measurement the absorber tube is irradiated with solar radiation, which shall be measured during the test.

The evaluation is performed for a cold receiver, near to ambient temperature.

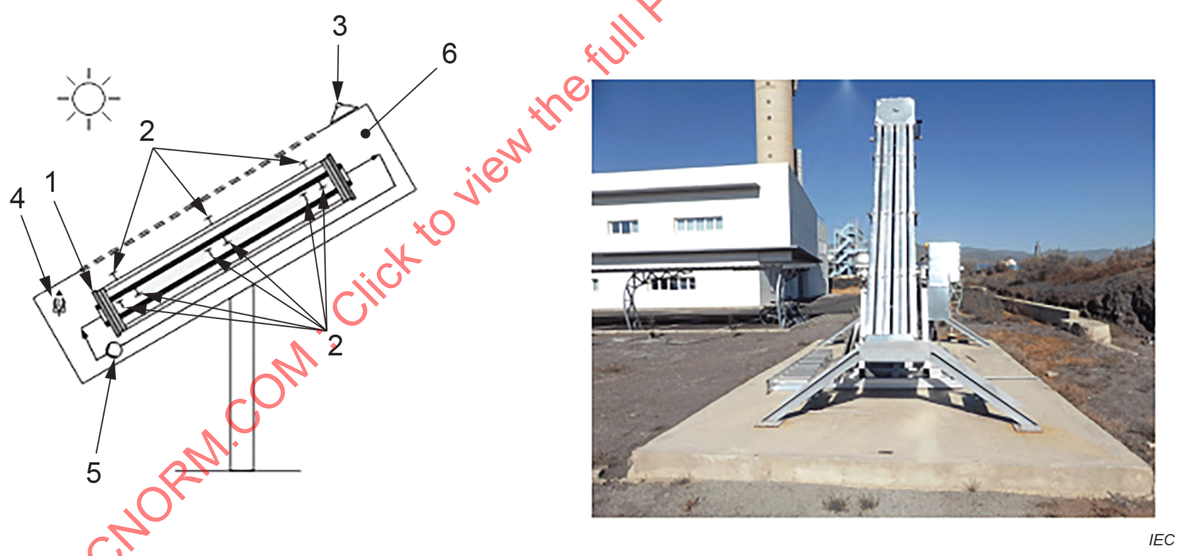
4.6.4.3 Equipment

The test bench shall have the following characteristics (see example in Figure 7):

- cavity to allocate the receiver tube: this cavity requires an opening slot of smaller width than the diameter of the absorber tube to guarantee direct normal irradiation to pass and strike on the absorber tube, but any radiation from other directions, specially reflected rays on surrounding surfaces do not strike on the tube. Total length of the opening slot shall be equal to the test sample;
- stand to support the cavity containing the receiver tube. The stand shall allow the positioning of the opening slot perpendicular to direct solar radiation during the test;
- system to recirculate water inside the tube during the test to avoid stratification of the fluid.

4.6.4.4 Instrumentation

- Pyranometer: non-linearity lower than 0,5 %, temperature dependence lower than 1 %, directional error lower than 10 W/m^2, spectral range 250 nm to 3 500 nm.
- Temperature sensors: Tolerance lower than ±0,5 °C in the measurement range.



a) Simplified scheme of the system

b) View of a real device (courtesy of CIEMAT-Plataforma Solar de Almería)

Figure 7 – Test bench for optical efficiency – Transient method

4.6.4.5 Test specimen and conditions

Before the test, the samples are cleaned according to the manufacturer's instructions.

The following data shall be measured:

- receiver geometry,
- temperature of the heat transfer fluid,
- glass envelope temperature,

- temperature of the absorber surface,
- irradiance on a test pyranometer,
- surrounding air temperature.

4.6.4.6 Procedure

The test consists of the measurement of the fluid temperature increase versus the time period when the glass envelope temperature is close to the absorber tube temperature and fluid temperature is near ambient temperature, i.e. heat losses are null. The test result is a combined optical efficiency value for the full length of the receiver under natural solar radiation, which includes properties of the glass envelope and its antireflective coating and the absorber's selective coating.

The sample receiver is positioned in the cavity of the test bench and oriented in north-south direction. The cavity has a longitudinal slot in its upper part at least equal to or less than that of the sample of absorber tube to be tested, and which is of sufficient width to allow all the direct solar radiation passing through it to focus on the wall of the absorber tube. The cavity is positioned perpendicular to the direct solar radiation, i.e. the slot aperture's plane is perpendicular to the direct solar radiation.

The fluid temperature increase shall be measured in steady-state radiation conditions, typically for 10 min, around the time when the temperature of the glass envelope (if there is a glass envelope, or the ambient temperature if there is no glass envelope) and the temperature of the absorber tube is the same, because at that time, the heat losses are null. The test shall be done close to solar noon to achieve constant solar radiation.

A receiver is considered to have been operating in proper conditions over a given measurement period if none of the experimental parameters indicated in Table 5 deviate from their mean values by more than the limits defined in Table 5 over the measurement period. To establish that an adequate measurement period exists, average values of each parameter taken over successive periods of 1 s shall be compared with the mean value over the measurement period (testing conditions shall be stationary).

Table 5 – Permitted deviation of measured parameters during a measurement period

Parameter	Permitted deviation from the mean value
Test irradiance	±1 %
Surrounding air temperature	±5 °C
Test fluid temperature vs. linear fitting (i.e. residuals)	±0,15 °C

4.6.4.7 Computation of collector output

The optical efficiency is calculated from energy balance that yields Equation (24):

$$\eta_{\text{rec,opt}} = \alpha \times \tau = \sum_i M_i \times c_{p_i} \times \left(\frac{\Delta T}{\Delta t}\right)_i \frac{1}{EA} = M \times c_{\text{p}} \times \left(\frac{\Delta T}{\Delta t}\right) \frac{1}{EA} \tag{24}$$

where

$\eta_{\text{rec,opt}}$ is the receiver optical efficiency (adimensional), α is the absorptance (adimensional) of absorber tube;

τ is the transmitance (adimensional) of the glass envelope (if there is a glass envelope);

i is each of the elements of the system;

M_i is the mass of element i of the system (in kg);

c_{p_i} is the specific heat capacity of element i of the system (in J/kg/°C);

M is the mass of the whole system (in kg);

c_p is the specific heat capacity of the whole system (in J/kg/°C), ΔT is the increase of temperature of fluid (in °C);

Δt is the time interval of the measurement (in s);

E is the global solar irradiance incident over the absorber tube (in W/m^2); and

A is the cavity slot aperture (in m^2).

For the test period, $\Delta T/\Delta t$ is obtained as the slope of the linear fitting curve $T(t)$.

A value of specific heat capacity of the system corresponding to the mean fluid temperature shall be used.

The difference between the fluid temperature in the absorber tube and the ambient temperature shall not exceed 10 °C; if this were not the case, heat losses could not be rejected.

4.6.5 Optical efficiency test (optional)

4.6.5.1 Objective

The purpose of the receiver optical efficiency test is to determine the optical absorption of solar radiation by a tubular receiver by evaluating the enthalpy increase of a fluid flow through the tube during the test. The test is performed in a solar simulator laboratory test bench. This test is non-destructive and provides in one measurement the receiver optical efficiency, in which absorptance, transmittance and useful active length are included.

This test is applicable with a solar simulator whose configuration and homogeneity shall be appropriate for the length and the diameter of the tubes to be measured; that is, the solar simulator shall ensure a high interception factor for the test irradiation.

The stability of the reference shall be ensured. This can be realized by comparison of the optical efficiency of the reference to two master references. This comparison is to be performed at least once a year.

4.6.5.2 General

The optical efficiency test measures the ratio of absorbed energy in the fluid and the incident irradiation energy. A standard sample is required as the measurement reference. Such a reference sample is a receiver of similar geometry or any derived secondary or working standard with stable and known properties. Comparative tests are possible with any set of samples of similar geometry. The evaluation is done by measuring the enthalpy flow of a water stream at ambient temperature of the fluid. During the measurement, the absorber tube is irradiated with a constant amount of focused light.

The test requires a focal line smaller than the diameter of the absorber tube, and longer than the overall length of the test specimen, with homogeneous intensity distribution along the focal line.

The evaluation is performed for a cold receiver, therefore geometry changes at elevated operating temperatures typical for this component shall be corrected for, for example, by determining the change in active length of the receiver due to bellows elongation or compression and bellows protection shield movement.

4.6.5.3 Instrumentation

A simulator shall have the following characteristics:

- Irradiance range: The simulator shall be capable of producing a mean irradiance over the receiver tube of at least 10 % of the nominal irradiance in real operation (the minimum irradiance shall be 0,5 kW/m for the current range for receivers > 40 mm absorber diameter).
- Spatial homogeneity: At any time, the irradiance at a point on the tube aperture shall not differ from the mean irradiance by more than ±10 % along the tube length.
- Time stability: At any time, the irradiance (mean during 10 s interval) shall not differ from the mean irradiance by more than ±5 %.
- Spectrum: As a light source, metal-halide lamps with CRI > 90 and outer bulb form UV-block glass, reflected by a solar mirror (low-iron glass, back rear-side coated with silver) are to be used.

4.6.5.4 Test specimen and conditions

Before the test the receiver will be initially inspected for damage according to the manufacturer's instructions; a visual check will be carried out focusing on the bellows, the coatings and any other abnormalities that may appear. Any findings will be recorded as part of the test report. In case of a major issue that raises doubts, the manufacturer should be contacted to establish that the test can be conducted on the receiver.

Before the test, the samples are cleaned according to the manufacturer's instructions. Bellows shields are to be installed according to the manufacturer's instructions (original parts, if available).

The following data shall be measured:

- receiver geometry;
- temperature of the heat transfer fluid at the tube inlet;
- temperature of the heat transfer fluid at the tube outlet;
- flow rate of the heat transfer fluid;
- irradiance on a test pyranometer;
- surrounding air temperature;
- glass envelope temperature (optional).

4.6.5.5 Procedure

The test consists of comparative enthalpy flow measurement of the cold-water stream through an irradiated receiver tube at constant testing conditions in the solar simulator. The test results in a relative combined optical efficiency value for the full length of the receiver under solar simulator light, including properties of the glass and its coating and the absorber coating.

The sample receiver is positioned in the linear focus of the test bench and the enthalpy increase of water running through the receiver at room temperature is measured. Pressure losses are neglected. The enthalpy increase in a reference sample receiver is measured the same day. This reference measurement provides the unit for the optical efficiency.

The enthalpy increase shall be measured in steady state, typically over a period of 5 min to 15 min.

A receiver is considered to have been operating in steady-state conditions over a given measurement period if none of the experimental parameters deviate from their mean values over the measurement period by more than the limits given in Table 6. To establish that a steady state exists, average values of each parameter taken over successive periods of 10 s shall be compared with the mean value over the measurement period (testing conditions shall be stationary).

Table 6 – Permitted deviation of measured parameters during a measurement period

Parameter	Permitted deviation from the mean value
Test irradiance	±1 %
Surrounding air temperature (indoor)	±5 °C
Fluid mass flow rate	±1,5 %
Fluid temperature at the collector inlet	±0,2 °C

4.6.5.6 Computation of collector output

The ratio of optical efficiency is calculated from tests of the sample (Q_{sample}) and reference ($Q_{reference}$) as:

$$Q = m_{wf} \times c_p(t_m) \times (t_{out} - t_{in}) \tag{25}$$

$$r_{sample} = Q_{sample} / Q_{reference}$$

For the test period, the mean r of all time intervals is calculated.

A value of specific heat capacity corresponding to the mean fluid temperature shall be used. If it is obtained from volumetric flow rate measurement, then the density shall be the correspondent value to the fluid temperature registered in the flow meter.

The difference between the initial fluid temperature in the tubes and the ambient temperature shall not exceed 10 °C. If this were not the case, radiation would have to be considered and thermal losses could not be rejected.

The optical efficiency of the sample $\eta_{rec,opt,sample}$ is

$$\eta_{rec,opt,sample} = r_{sample} \times \eta_{rec,opt,reference} \tag{26}$$

NOTE Owing to the expansion of the absorber tube with increasing temperature, receiver length and active length can change as a function of temperature. As the receiver is mainly operated at elevated temperature, the change in optical efficiency is modelled as a geometric effect.

Optical efficiency is approximated with

$$\eta_{rec,opt} \approx \alpha\ \tau\ \psi_{net} \tag{27}$$

where

ψ_{net} is the fraction of active length to receiver length $\psi_{net} = l_{active} / l_{rec}$.

Absorptance α of the absorber and transmittance τ of the glass envelope are assumed to be constant with temperature. Furthermore only radiation of normal incidence is considered. The change in optical efficiency is a result of a change in active length l_{active} and receiver length l_{rec} as a function of temperature:

$$\eta_{\text{rec,opt}}(T) \approx \alpha\,\tau\,\frac{l_{\text{active}}(T)}{l_{\text{rec}}(T)} \tag{28}$$

4.7 Durability tests for the receiver

4.7.1 General

Information on the materials used in solar thermal receivers is provided in Annex A, in the test report, which includes the technical characteristics and dimensions of the materials.

4.7.2 Antireflective glass envelope coating durability tests

4.7.2.1 Stationary abrasion resistance test on glass envelope surface

4.7.2.1.1 Objective

The abrasion test is an accelerated ageing test. It is meant to simulate the mechanical wear of the glass coating in the solar field due to cleaning, sandstorms or other mechanical forces on the glass surface over the lifetime of the component. This test is similar to the abrasion test of ISO 9211-4.

This test consists of rubbing the dry glass tube with an abrasive rubber. The type of abrasive rubber, the load applied on the glass surface and the number of lengthwise rubbing cycles could cause degradation and peeling off of the antireflective coating.

An abrasion head is moved with low pressure on the glass surface in a straight line back and forth. The abrasion head material consists of an abrasive material inside a rubber matrix. One cycle is defined as the movement of the grinding head once forth and back. The movement of the abrasion head produces grinded stripes on the glass surface, where the light transmittance is affected by the scratches.

The evaluation of the light transmittance of treated material is performed with measurements of transmittance on the treated surface area and compared to the original value.

4.7.2.1.2 Equipment and assembly

The test is a linear back-and-forth movement of an abrading rubber over the glass surface, typically performed with an apparatus with a counter in order to move the rubber in a constant manner over the surface.

The measurements of transmittance will be performed by an UV-VIS_NIR spectrophotometer before and after each set of test cycles, according to 4.6.1.

The test equipment includes:

- a holder for the glass tube or piece to be tested;
- a holder for the abrasive rubber attached to a device that moves longitudinally back and forth over the sample;
- an abrasive rubber according to MIL-E 12397 (diameter 6 mm);
- a weight/pressure controller;
- a sandblasted glass rod or a sandpaper grit P600.

The equipment is shown in Figure 8.

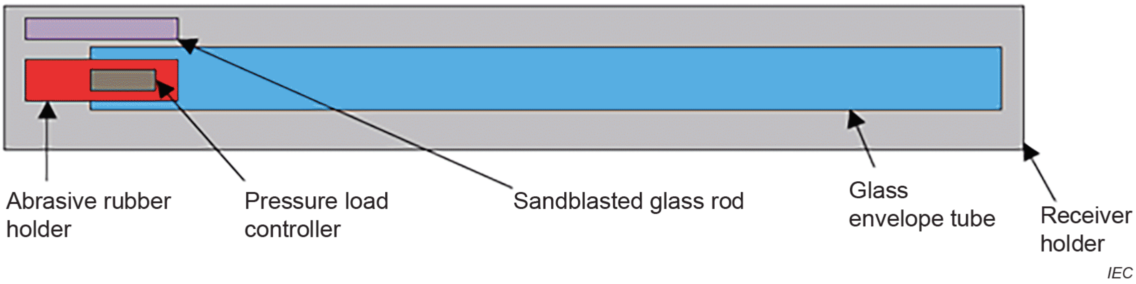


Figure 8 – Schematic of abrasion equipment

The sandblasted glass rod is used to resurface the abrasive rubber before and after testing, in order to obtain reproducible test results.

In addition to the schematic in Figure 8, if a glass tube is used for the test, the test equipment shall be able to rotate the receiver (see Figure 9). The result of this rotation shall be a glass test surface of at least 45 mm × 40 mm where the transmittance can be measured.

Dimension in millimeters

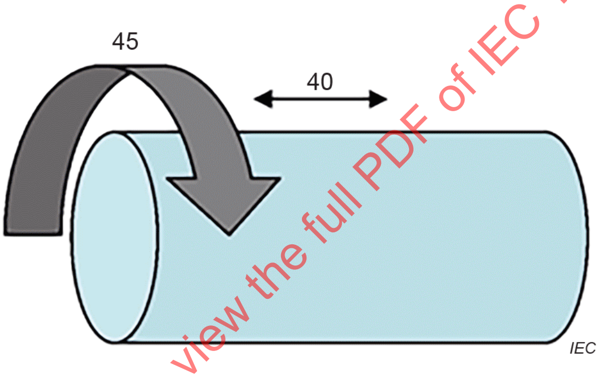


Figure 9 – Drawing of receiver rotation in abrasion equipment for a tube or piece

The specimen shall be placed in the holder in such a way that it is held rigidly. The abrasive rubber holder is lowered, positioning it on the glass surface with the antireflective coating. The load, which may be varied for force or pressure, is applied perpendicular to the glass surface.

4.7.2.1.3 Test conditions

Before testing, the glass tube or sample shall be cleaned using either ethanol or deionized water; it is up to the receiver manufacturer to decide which cleaning material should be used from among the options mentioned. The optics of the surface to be treated shall also be analysed, measuring the transmittance of the test specimen in the area where the test will be applied. The measurement method used shall be indicated in the report. (The standard for measuring transmittance is under consideration.)

4.7.2.1.4 Procedure

– Preparation of the abrasive rubber:

  The abrading rubber is prepared before each test (each set of cycles and before every turn) with at least 5 cycles on sand glass rod or sandpaper grit, according to the rubber manufacturer's instructions. The purpose of this is to create reproducible starting conditions by removing remaining particles attached to the rubber from previous tests. Also it is important to parallelize the grinding rubber surface to the glass surface, so that the entire bottom surface of the rubber is in contact with the glass, making sure the rubber touches the glass with a surface and not with a point. The easiest way to ensure parallel surfaces is to apply the sand glass rod or sandpaper grit directly to the sample to be tested. After the preparation of the grinding rubber, all loose material shall be removed from the abrasive rubber and the sandblasted glass rod or sandpaper grit, for example, by using pressurized air or a smooth brush.

– Abrasion:

For the test, the grinding rubber is moved over the glass for a number of cycles. At minimum, the following list of cycles shall be carried out: 5, 10, 20, 50, 100. A higher number of cycles can be chosen, and the laboratory can be instructed accordingly. It needs to be ensured that the cycles are continued at the exact same position on the sample after each transmittance measurement.

Three different samples (or three different areas of the same sample) are tested after each number of cycles. One cycle consists of two strokes: one back and one forth. The cleaning procedure between the tests should be the same as the initial cleaning procedure.

After applying the predefined number of cycles, the tube sample is turned in a circular direction by an angle which corresponds to the width of the abrasive rubber, and rubbing is started up again. The abrasive rubber needs to be refaced before each use after rotation. This procedure is repeated as many times as necessary to reach 45 mm × 40 mm or the area necessary to perform transmittance measurements.

This test shall be performed under the following conditions:

- abrasive rubber, specifications as per MIL-E-12397 (diameter 6 mm);
- load weight, 350 g ± 10 g;
- linear strokes with a minimum length of 40 mm ± 2 mm;
- frequency: 7 cycles/min;
- linear direction: the tube length;
- ambient temperature conditions.

The evaluation of transmittance shall be performed on the tested area of the sample.

The test shall be performed on at least three different areas of the tube or sample. In the case of a tube, it is recommended that the test be performed at both ends and in the middle.

4.7.2.1.5 Evaluation

After the number of cycles on the same area of the sample have been carried out, the treated surface shall be cleaned with deionized water and alcohol (ethanol, isopropanol, etc.) with a sprayer and dried with a microfiber or cotton cloth.

Then a first visual inspection shall be made to evaluate any damage to or peeling of the antireflective coating.

Finally, the optics of the surface shall be evaluated by measuring its transmittance using the same method as that used before the test. The transmittance shall be measured in the centre of the treated area and in all treated areas. Transmittance shall be measured at least three times in the centre of the treated area

The measured transmittance before and after testing shall be given in the test report.

The test cycles can be stopped when the transmittance from one to the next number of cycles does not decrease any more (coating completely removed). When comparing several samples, the evaluation should be done on the same testing device to ensure a full comparison of uncertainties and between results.

4.7.2.1.6 Test report

See Annex A.

4.7.2.2 Condensation test

4.7.2.2.1 Objective

The purpose of this test is to determine the possible degradation of the antireflective coated glass envelope of a solar receiver under constant exposure to a condensation-water atmosphere.

In this test the resistance of the antireflective layer is evaluated under simulated natural climate conditions of ageing.

The test is based on the condensation test of ISO 6270-2:2017.

4.7.2.2.2 Preparation of test specimens

Samples shall be taken from the supplier of solar receivers to be installed in the solar field. It is recommended that the size of the samples be 100 mm × 100 mm. Other sizes may be used as long as they are larger than 100 mm × 100 mm and it is expressly indicated in the report on results. Place the sample in the chamber on its ends with the convex side facing up.

Before testing, any prior defect in the samples and their transmittance shall be measured following the optical characterization test described in 4.6.

The samples shall be carefully cleaned before testing, following the manufacturer's specifications.

4.7.2.2.3 Instrumentation or equipment

The equipment shall be as described in Clause 8 of ISO 6270-2:2017. The inside of the equipment shall be made of chemically inert materials and thermally insulated.

Equipment shall be maintained in a room at a controlled constant temperature between 21 °C to 25 °C. The equipment shall be provided with a continuous temperature data acquisition system.

4.7.2.2.4 Procedure

Samples shall be subjected to a constant temperature of 40 °C ± 2 °C and relative humidity of 100 % to 5 % as per Clause 7 and Clause 9 of ISO 6270-2:2017.

4.7.2.2.5 Evaluation and test report

The following parameters shall be reported after the test:

- solar weighted transmittance loss in the wavelength range 300 nm to 2 500 nm;
- graph of the initial and final transmittance spectrum in the wavelength range 300 nm to 2 500 nm;
- visual or microscopical degradation effects.

4.7.3 Impact resistance test (optional)

4.7.3.1 Objective

The purpose of this test is to determine the extent to which the receiver tube can resist the effects of heavy impact caused by hail.

The test can be carried out by either of two different methods, that is, with the use of ice balls or steel balls. As the loss of energy on impact is different for ice balls and steel balls, each method shall be used for a different quantitative purpose.

The ice balls lose energy on impact, and therefore the impact is more like the real effect of impact by hail. This method is preferable for resistance testing.

On the other hand, the steel balls do not lose deformation energy on impact. The limit of breakage from impact shall be determined with this test.

4.7.3.2 Impact resistance test with ice balls

4.7.3.2.1 General

NOTE The test simulates better the real conditions of hail impact on the receivers than the same test using steel balls.

4.7.3.2.2 Equipment

a) Moulds shall be made of a suitable material for making round balls of ice with the required diameter. The diameters are shown in Table 7.
b) A freezer with temperature controlled at −10 °C ± 5 °C.
c) A freezer for storing the ice balls at a temperature of −4 °C ± 2 °C.
d) A launcher able to propel an ice ball at a speed as shown in Table 7 ±5 % and to hit the receiver tube in the specified impact zone.
e) A rigid frame to hold the sample with the impact surface perpendicular to the trajectory of the ice ball projected. The holder shall be rigid enough to make any distortion or deformation at the moment of impact insignificant.
f) A scale to determine the mass of the ice balls with a standard uncertainty of ±2 %.
g) An instrument for measuring the speed of the ice ball with a standard uncertainty of ±2 m/s. The speed sensor shall not be placed more than 1 m away from the sample.

4.7.3.2.3 Ice balls

The ice balls shall be made of water. They shall contain absolutely no air bubbles or any cracks visible to the naked eye. The ball's diameter shall be 25 mm. The test procedure shall be carried out with ice balls at a temperature of −4 °C ± 2 °C.

Table 7 – Ice ball test mass and speed

Diameter mm	Mass g	Speed m/s	Kinetic energy J
25	7,53	23,0	2,0

4.7.3.2.4 Procedure

a) With the moulds and the freezer, make enough ice balls of the size required for the test, including some for preliminary adjustment of the launcher.
b) Examine each ball for cracks, measure their diameter and mass. An acceptable ball shall comply with the following criteria:
   - no cracks visible to the naked eye;
   - diameter ±5 % of that required (see Table 7 for requirements);
   - mass within ±5 % of that required (see Table 7 for requirements);
c) Place the balls in the storage container and leave them there for at least 1 h before use.

d) Make sure that all launcher surfaces that will come into contact with the ice balls are at ambient temperature.

e) Launch a number of test balls following step (g) and adjust the launcher to the launching speed measured with the speed sensor so that the position shown is ±5 % of the test speed given in Table 7.

f) Install the receiver tube at ambient temperature in the support specified with the impact surface perpendicular to the trajectory of the ice ball.

g) Take an ice ball from the storage container and place it in the launcher. Adjust the point of impact and shoot at that point. The time between extraction of the ice ball from the mould and its impact shall not exceed 60 s.

4.7.3.2.5 Test conditions

The point of impact shall be at a distance less than 10 cm and more than 5 cm from the glass-metal weld at the end of the receiver tube.

The test procedure shall begin at the lowest ice ball launch speed or that specified by the manufacturer. The test procedure for each speed shall consist of four shots. The shot shall be perpendicular to the surface of the glass tube.

4.7.3.3 Resistance to impact with steel balls (or test for quantifying the limit of breakage by impact)

4.7.3.3.1 Equipment

The tube shall be mounted horizontally on a support, which shall be strong enough so that any distortion or deflection at the time of impact will be negligible.

4.7.3.3.2 Steel balls

The steel ball shall have a mass of 150 g ± 10 g and be used at the following series of test heights: 0,4 m, 0,6 m, 0,8 m, 1,0 m, 1,2 m, 1,4 m, 1,6 m, 1,8 m, and 2,0 m.

4.7.3.3.3 Test conditions

Steel balls are used to simulate heavy impact. Impact is directed horizontally by a pendulum or by dropping the ball vertically from the specified heights on the glass tube. The height of the ball is the vertical distance between the point from which the ball is launchedand the horizontal plane containing the point of impact.

The first point of impact shall be no further than 10 cm from the end of the glass to metal connection, but shall be moved several millimetres each time a steel ball is released. It shall be dropped on the receiver tube 10 times from the first test height, then 10 times from the second test height, etc., until the maximum test height is reached (the maximum height shall be according to the manufacturer's specifications or, if none is stated, 2 m). The test shall end when the tube shows some damage or has resisted the impact of 10 steel balls released from the maximum test height.

4.7.3.3.4 Evaluation

The tube shall be inspected for damage or degradation. In particular, any change in colour of the absorber tube and/or the getter condition shall be inspected to detect any loss of vacuum.

The results of the inspection shall be recorded along with the height from which the ball was launched or the speed at which it was shot and the number of impacts that caused the damage.

4.7.3.3.5 Test report

See Annex A.

4.7.4 External and/or internal thermal shock test

These testing procedures are currently being developed and have not yet been validated; they are not available at any of the third-party facilities. A reference to an appropriate procedure will be presented in a future revision of this document.

4.7.5 Thermal stability test of absorber selective coatings for full receiver tube

4.7.5.1 Objective

The purpose of this test is to establish a qualification procedure for evaluating the thermal stability in air and/or vacuum of the selective absorber coatings of a solar receiver.

The scope of application of this test covers receivers for both parabolic trough and Fresnel technology solar thermal power plants, as long as these receivers use selective coatings.

4.7.5.2 General

The solar receivers of solar thermal technologies work at very high operating temperatures, usually under vacuum, and these conditions can produce chemical and physical changes on the absorber surfaces, giving rise to losses in their optical performance.

The heat losses and optical characterization of the receiver are the parameters used to evaluate the stability or degradation of the selective absorber coatings.

4.7.5.3 Test procedure

The thermal stability test is an accelerated ageing test of the selective absorber coating of the receiver.

The receiver tube to be tested shall be placed horizontally in the test support frame holders.

There are several methods for reaching a certain temperature in the receiver. For example, by Joule effect, by electrical heating elements or by IR resistance attached to a copper tube inserted inside the absorber tube, see further details in 4.5.

The test room shall be suitably insulated or sufficiently separated from other electronic equipment that might be found around it and which could influence acquisition of measurement data. Similarly, any electronic equipment shall be grounded.

The temperature of the surrounding air shall be 20 °C ± 10 °C. The ambient temperature sensor shall be placed not more than 2 m from the sample, at a place where it is not affected by hot spots or air currents.

The test is performed at a minimum absorber temperature of 100 °C above the maximum operating temperature as defined by the manufacturer. The duration of the test is 1 000 h.

For the first heat-up above the maximum operating temperature defined by the manufacturer, the heat-up rate for T > max. operating temperature shall be < 0,05 °C/min.

At least four temperature sensors spread symmetrically along the tube shall control the temperature of the stainless-steel tube and at least one additional sensor shall control the glass tube temperature.

The receiver shall be kept for 48 h at specified testing temperature after reaching temperature homogeneity of the steel tube.

The receiver shall be at the test temperature for at least 1 000 h (if a period longer than 1 000 h has been agreed with the manufacturer, that value will be indicated in the test report).

After 1 000 h, optical measurements and heat loss testing shall be carried out and compared to the results measured on the same receiver(s) before conducting the thermal stability test (see 4.4 and 4.7).

During the waiting period and while taking measurements, the stability of temperatures measured shall be monitored according to the requirements in Table 8.

Table 8 – Monitored parameters during waiting period

Parameter to be monitored	Stability requirement
Absorber tube temperatures	±2 °C
Glass envelope tube temperatures	±5 °C
Ambient temperatures	20 °C ± 10 °C

The cooling process consists of:

- switching off the heaters or energy source;
- cooling the tube to room temperature.

The heat loss and optical characterization measurements will be performed after 1 000 h. These measurements can also be performed after other time intervals. Time intervals shall be indicated in the test report.

4.7.6 Thermal stability of selective absorber coatings for coated stainless-steel samples

4.7.6.1 Objective and references

This Subclause 4.7.6 describes an accelerated ageing procedure for the selective absorber coatings of solar receivers; the procedure is based on Arrhenius test calculations to determine the long-term thermal stability of the coatings.

This test is based on the ageing test of ISO 22975-3, where it is used as a qualification procedure for evaluating the thermal stability of selective solar absorber coatings at lower temperatures.

Therefore, an adaptation of the procedure detailed in ISO 22975-3 for higher temperature selective solar coatings used in parabolic-trough or Fresnel technology is presented here.

4.7.6.2 General

High-temperature ageing is frequently used in many technical applications for the assessment of the thermal stability of materials. A high temperature accelerates all kinds of processes, normally leading to an increased rate of degradation of materials. This change in degradation is described by the Arrhenius law.

This test can provide the activation energy of the degradation process of the selective coatings, information on the lifetime of the coating at a selected temperature, and the maximum temperature at which a coating can operate without exceeding a certain value of the performance criterion for a selected time period.

Where, $\Delta\alpha$ is the change in the solar absorptance defined as:

$$\Delta\alpha = \alpha_t - \alpha_i \tag{29}$$

with α_t equal to the value of the solar absorptance at the actual time of the test or at service, and with α_i equal to the initial value of solar absorptance and where $\Delta\varepsilon$ is the change in the thermal emittance, and

$$\Delta\varepsilon = \varepsilon_t - \varepsilon_i \tag{30}$$

with ε_t equal to the value of the thermal emittance calculated at the maximum operating temperature specified by supplier/manufacturer at the actual time of the test or at service and with ε_i equal to the initial value of thermal emittance.

Assuming that the degradation of the selective absorber coating follows a mechanism based on Arrhenius law, the degradation rate should be defined by Equation 31:

$$K = Ae^{\left(-\frac{E_a}{RT}\right)} \tag{31}$$

where

K is the degradation rate of the process,

A is a characteristic constant of each process,

E_a is the activation energy of the process,

R is the universal gases constant and

T is the absolute temperature.

$$lnK = -Ea / R \times 1 / T + A \tag{32}$$

From the slope of the plot (lnK vs $1/T$) the activation energy of the degradation process can be obtained.

4.7.6.3 Test procedure

For durability testing, samples which are sections of the solar receiver tube under study with an absorber surface area preferably larger than (50 × 50) mm shall be prepared. For execution of the complete programme of durability tests of this recommended procedure, a minimum of 15 test samples are required.

The test samples shall be managed in order to guarantee that they are not damaged or altered by external conditions such as humidity or oxidation or other external factors not present in vacuum condition.

The tube manufacturer shall indicate which kind of storage and handling have to be adopted.

Before carrying out durability testing of the absorber surface, all test specimens shall be characterized with respect to their value for solar absorptance (300 nm to 2 500 nm) and thermal emittance (2 500 nm to 20 000 nm) as defined in 4.7.1. To be qualified for testing, the set of test specimens shall present a standard deviation for the determined values of solar absorptance of less than 0,005 and for the determined values of thermal emittance a standard deviation of less than 0,015.

Test samples (three samples per selected temperature) shall be heated in vacuum ovens to at least three different temperatures above the service temperature of the coating (i.e. to 100 °C, 125 °C, 150 °C, 175 °C above maximum operating temperature). Testing at additional temperatures would provide more information and make the results more accurate but would take more time; the decision to do so is therefore up to the supplier. Minimum testing time should be 600 h, although a longer time is recommended to obtain more information, for instance, 3 000 h. However, the final duration of the experiment shall be determined in order to obtain a correct evaluation of the degradation rate. The temperature in the vacuum oven shall be homogeneous and stable throughout the experiments with an uncertainty no larger than ±5 °C. As the coatings under study are designed to operate in vacuum, no heating should be applied to the samples until vacuum is below 5 mbar × 10^{-5} mbar and the recommendations of the manufacturer regarding storage and handling of the samples shall always be satisfied.

In order to monitor the degradation of the samples over time, the weighed solar absorptance and thermal emittance is calculated from the total solar reflectance (TSR) at the beginning of the test and at different stages during the heating process, at doubling intervals of time (for instance, t = 0, (10, 20, 40, 80, 160, 320, 640, 1 280 and 2 560) h). To measure reflectance during the heating process, heating is stopped, ovens allowed to cool to room temperature and reflectance in the full wavelength range is measured (300 nm to 25 000 nm).

The PC variation over time for each testing temperature shall be calculated using a linear fit to determine the ΔAlpha/Δt and ΔEpsilon/Δt.

With the degradation rates obtained in accordance with the above method, the Arrhenius plot shall be computed ln(ΔAlpha/Δt and ΔEpsilon/Δt) versus (1/T) and, along with this value, the activation energy E_a, that will be the test final result.

In addition, the activation energy should be reported to allow for the calculation of the lifetime of the coating.

If no degradation is observed during the tests described above in this Subclause 4.7.6.3, the result should be that the activation energy is above that of the degradation test requirements of this document.

Pieces should be taken from different areas on the receiver to ensure that the homogeneity of the coating is also tested.

In addition to the activation energy of the process, the Arrhenius calculation provides information on the lifetime of a coating. This coating lifetime can be defined as operation time where the coating does not exceed certain limits of absorptance and emittance at a selected temperature. These limits of absorptance and emittance are defined by the supplier and/or end-user companies.

4.7.7 Thermal cycling test

4.7.7.1 Objective

The purpose of this test is to establish a qualification procedure for evaluating the thermal stability in air and/or vacuum of the bellows, and welding, as well as the selective absorber coatings of a solar receiver.

The scope of application of this test covers receivers for both parabolic-trough and Fresnel technology solar thermal power plants, as long as these receivers use bellows, welding and selective coatings

4.7.7.2 General

The solar receivers of solar thermal technologies work at very high operating temperatures, usually under vacuum, and these conditions can produce chemical and physical changes on the absorber surfaces as well as mechanical wear on the bellows and welding, giving rise to losses in their optical performance or causing destructive damage to the entire receiver (i.e. loss of vacuum).

Visual inspection as well as heat losses and optical characterization tests of the receiver are the parameters used to evaluate if the receiver is still mechanically intact as well as the stability or degradation of the selective absorber coatings (for heat loss and optical characterization see 4.4 and 4.7).

4.7.7.3 Test procedure

The receiver tube to be tested shall be placed horizontally in the test support frame holders.

There are several methods for reaching a certain temperature in the receiver. For example, by Joule effect, by electrical heating elements or by IR resistance attached to a copper tube inserted inside the absorber tube, see further details in 4.5.

The test room shall be suitably insulated or sufficiently separated from other electronic equipment that might be found around it and that could influence the acquisition of measurement data. Similarly, any electronic equipment shall be grounded.

The temperature of the surrounding air shall be 20 °C ± 10 °C. The ambient temperature sensor shall be placed not more than 2 m from the sample, at a place where it is not affected by hot spots or air currents.

At least four temperature sensors spread symmetrically along the tube shall monitor the temperature of the stainless-steel tube and at least one additional sensor shall monitor the glass tube temperature.

In order to create the cycling test, the absorber's temperature is cyclically changed.

At least 100 cycles of temperature change (if more than 100 cycles have been agreed with the manufacturer, this will be indicated in the test report) from 200 °C to 100 °C above the maximum operating temperature, as defined by the manufacturer.

The limits for temperature gradients are:

- heat-up rate < 5,00 °C/min at heat-up for T < max. operating temperature as defined by the manufacturer;
- heat-up rate < 2,00 °C/min at heat-up for T > max. operating temperature as defined by the manufacturer.

At first heat up above operating temperature, the heat-up rate for T > maximum operating temperature shall be < 0,05 °C/min.

4.7.8 Bellows test

4.7.8.1 Purpose and scope of application

The purpose of 4.7.8 is to specify a test method to determine the durability of the receiver tube bellows (bellows that connect the metal absorber tubes and the glass envelope tube) against mechanical fatigue.

4.7.8.2 Test performance

4.7.8.2.1 General

The bellows is the airtight connection of the absorber tube and the glass envelope. Depending on the specific receiver design, the bellows might also have to support the weight of the glass envelope. At operating temperature, the absorber of the receiver expands due to its high coefficient of thermal expansion while the glass envelope barely changes its length. As the receiver temperature is significantly reduced during the night, the bellows experiences expansion and compression every day the field is operated.

The bellows has to withstand this stress without leakage in order to keep receiver efficiency high over the lifetime of the receiver. A vacuum leak significantly increases the heat loss of the receiver. Leaks are detected by monitoring heat loss.

Before the test, the receiver will undergo an initial inspection for damage according to the manufacturer's instructions; a visual check will be carried out focusing on the bellows, the coatings, and any other abnormalities that may appear. Any findings will be recorded as part of the test report. In case of a major issue that raises doubts, the manufacturer should be contacted to establish whether the test can be conducted on the receiver. Only intact samples are suitable for testing.

4.7.8.2.2 Test bench setup and methodology

A heating element is inserted into the receiver and the receiver is heated to a set temperature leading to half the maximum bellows expansion. The absorber tube is fixed to the test bench at one of its ends, connecting the absorber to the test bench and supporting the weight of the absorber tube and the heater module. The weight of the glass envelope is supported by the bellows, as in operation. The absorber tube ends are heated with additional heating elements up to the specified maximum service temperature so that the bellows performs at similar temperature as in field operation. Push-pull shafts on both sides of the receiver are connected to the envelope clamp and move the envelope back and forth. Bearings allow the envelope to freely move up and down and pitch. A counterweight compensates for the weight of the envelope clamp. The glass tube is moved by the clamps with an eccentric drive.

An example of the concept is given in Figure 10. A push-pull shaft is moved back and forth by a motor with connecting rod and eccentric shaft. Once the absorber has reached the temperature of testing, vertical slabs are connected to the linear shaft on both sides of the receiver tube, the motor is activated, and the slabs push the glass envelope back and forth. Operation speed is 1 cycle/s.

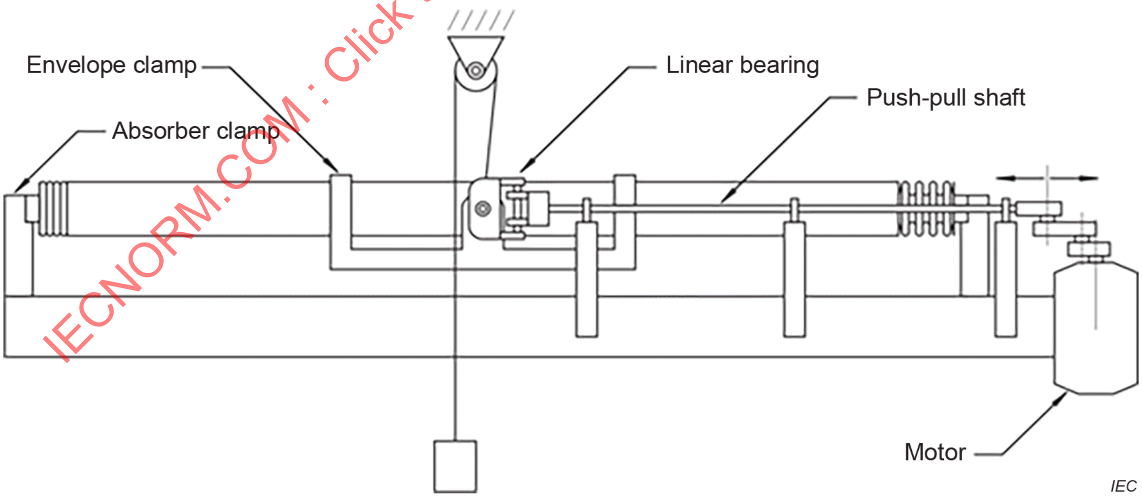


Figure 10 – Example of a test bench for testing bellows fatigue

4.7.8.3 Measurement instrumentation and methods

4.7.8.3.1 Temperature measurements

The instrumentation comprises a push-pull mechanism with a control cabinet housing power supplies, safety switches and a data acquisition system, and PC with a program displaying measurement data and controlling the heater powers. Heating power is monitored by using the heater power supply control signal and assuming constant heater resistance and constant supply voltage.

The expanded uncertainties of the average temperatures of each sensor shall be less than:

- ±2 °C for the absorber tube;
- ±2 °C for the glass envelope tube;
- ±1 °C for ambient or surrounding air.

The expanded uncertainties of the means of the temperatures found by the sensors shall be less than:

- ±10 °C for the absorber tube;
- ±10 °C for the glass envelope tube;
- ±1 °C for ambient or surrounding air.

The thermal contact of the sensor at the surface shall be suitable to ensure the measurement.

4.7.8.3.2 Power measurements

The power logger should have a minimum accuracy of 2 % to 3 % of the full-scale reading.

Power sensors should have been calibrated during the year prior to the test.

4.7.8.3.3 Data acquisition frequency

Temperature sensor recording frequency shall be no less than four times the response time of the slowest sensor, and the minimum number of records should ensure the statistical representativeness of the test. Data shall be acquired at least every minute. A counter serves to measure the exact number of performed expansion cycles.

4.7.8.4 Test procedure

4.7.8.4.1 Test method

The receiver shall be exposed to a minimum of 15 000 cycles of expansion and compression of the bellows. Stop after 10 000 cycles for 24 h to check if the vacuum is still satisfactory according to the vacuum indicator on the receiver; if yes, continue for another 5 000 cycles. The thermal loss test shall be carried out before and after the bellows test (after 15 000 cycles). If heat loss does not increase more than 30 % during the test and during the 24-h waiting period after the cycling, the test is considered successfully passed. The 24-h waiting period is necessary in order to be able to also detect microscopic leaks. The threshold of 30 % is chosen to take into consideration experimental uncertainties in the presented test bench.

The maximum difference allowed in heat losses is an increase of 30 % at all temperatures.

A cycle is considered to be the total expansion of one edge, causing the total compression of the other edge, followed by the total compression of the first mentioned edge, causing the total expansion of the second. This way, both edges will have been subjected to a whole expansion-compression period. The expansion/compression amplitude (in mm) shall be determined for the specific maximum temperature, as the maximal temperature the receiver is exposed to and 25 °C as reference temperature and the minimum temperature the receiver is exposed to.

4.7.8.4.2 Measurements

At least the following data should be measured.