INTERNATIONAL STANDARD

# ISO 9806-1

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# Test methods for solar collectors —

## Part 1:
Thermal performance of glazed liquid heating collectors including pressure drop

*Méthodes d'essai des capteurs solaires —*

*Partie 1: Performance thermique des capteurs vitrés à liquide, chute de pression incluse*

Reference number
ISO 9806-1:1994(E)

# Contents



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# Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 9806-1 was prepared by Technical Committee ISO/TC 180, *Solar energy*, Subcommittee SC 5, *Collectors and other components*.

ISO 9806 consists of the following parts, under the general title *Test methods for solar collectors*:

— *Part 1: Thermal performance of glazed liquid heating collectors including pressure drop*

— *Part 2: Qualification test procedures*

— *Part 3: Thermal performance of unglazed liquid heating collectors (sensible heat transfer only) including pressure drop*

Annex A forms an integral part of this part of ISO 9806. Annexes B, C, D, E, F and G are for information only.

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# Test methods for solar collectors —

## Part 1:
## Thermal performance of glazed liquid heating collectors including pressure drop

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## 1 Scope

**1.1** This part of ISO 9806 establishes methods for determining the thermal performance of glazed liquid heating solar collectors. These tests are intended for use as part of the sequence of tests specified in ISO 9806-2.

**1.2** This part of ISO 9806 provides test methods and calculation procedures for determining the steady-state and quasi-steady-state thermal performance of solar collectors. It contains methods for conducting tests outdoors under natural solar irradiance and for conducting tests indoors under simulated solar irradiance.

**1.3** This part of ISO 9806 is not applicable to those collectors in which the thermal storage unit is an integral part of the collector to such an extent that the collection process cannot be separated for the purpose of making measurements of these two processes.

**1.4** This part of ISO 9806 is not applicable to unglazed solar collectors nor is it applicable to tracking concentrating solar collectors. (See ISO 9806-3 for a test method for unglazed collectors.)

## 2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO 9806. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO 9806 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 9060:1990, *Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation.*

ISO 9459-1:1993, *Solar heating — Domestic water heating systems — Part 1: Performance rating procedure using indoor test methods.*

ISO 9806-2:—[1], *Test methods for solar collectors — Part 2: Qualification test procedures.*

1) To be published.

ISO 9806-3:—[1)], *Test methods for solar collectors — Part 3: Thermal performance of unglazed liquid heating collectors (sensible heat transfer only) including pressure drop.*

ISO 9845-1:1992, *Solar energy — Reference solar spectral irradiance at the ground at different receiving conditions — Part 1: Direct normal and hemispherical solar irradiance for air mass 1,5.*

ISO 9846:1993, *Solar energy — Calibration of a pyranometer using a pyrheliometer.*

ISO 9847:1992, *Solar energy — Calibration of field pyranometers by comparison to a reference pyranometer.*

ISO/TR 9901:1990, *Solar energy — Field pyranometers — Recommended practice for use.*

WMO, *Guide to Meteorological Instruments and Methods of Observation*, 5th edn., WMO-8, Secretariat to the World Meteorological Organization, Geneva, 1983, Chapter 9.

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## 3 Definitions

For the purposes of this part of ISO 9806, the following definitions apply.

**3.1 absorber:** Device within a solar collector for absorbing radiant energy and transferring this energy as heat into a fluid.

**3.2 absorber area** (of a nonconcentrating solar collector)**:** Maximum projected area of an absorber.

**3.3 absorber area** (of a concentrating solar collector)**:** Surface area of the absorber which is designed to absorb solar radiation.

**3.4 angle of incidence** (of direct solar radiation)**:** Angle between the line joining the centre of the solar disc to a point on an irradiated surface and the outward-drawn normal to the irradiated surface.

**3.5 aperture:** Opening of a solar collector, through which the unconcentrated solar radiation is admitted.

**3.6 aperture area:** Maximum projected area through which the unconcentrated solar radiation enters a collector.

**3.7 collector area, gross:** Maximum projected area of a complete solar collector, excluding any integral means of mounting and connecting fluid pipework.

For an array or assembly of flat plate collectors, evacuated tubes or concentrating collectors, the gross collector area includes the entire area of the array, i.e. also borders and frame.

**3.8 collector, concentrating:** Solar collector that uses reflectors, lenses or other optical elements to redirect and concentrate the solar radiation passing through the aperture onto an absorber, the surface area of which is smaller than the aperture area.

**3.9 collector efficiency** (of a solar thermal collector)**:** Ratio of the energy removed from a specified reference collector area (gross or absorber) by the heat transfer fluid over a specified time period, to the solar energy incident on the collector for the same period, under steady-state conditions.

**3.10 collector, evacuated tube [tubular]:** Solar collector employing transparent tubing (usually glass), with an evacuated space between the tube wall and the absorber.

The absorber may consist of an inner tube of another shape, with means for removal of thermal energy. The pressure in the evacuated space is usually less than 1 Pa.

**3.11 collector, flat plate:** Nonconcentrating solar collector in which the absorbing surface is essentially planar.

**3.12 heat transfer fluid:** Fluid that is used to transfer thermal energy between components in a system.

**3.13 irradiance:** At a point on a surface, the radiant energy flux incident on an element of the surface, divided by the area of that element.

Irradiance is normally expressed in watts per square metre.

**3.14 irradiance, direct solar:** Radiant energy flux, incident on a given plane receiving surface from a small solid angle centred on the sun's disc, divided by the area of that surface.

It is expressed in watts per square metre.

NOTE 1 The inclination of the surface should be specified, e.g. horizontal. If the plane is perpendicular to the axis of the solid angle, then direct normal solar irradiance is received. For appropriate radiometers of modern design, the small solid angle (field-of-view angle) is less than 6°.

**3.15 irradiance, global solar:** Radiant energy flux, incident on a given plane receiver surface, from a solid angle of 2π sr, divided by the area of that surface.

It is expressed in watts per square metre.

NOTE 2 The inclination of the surface should be specified, e.g. horizontal. Solar irradiance is often termed "incident solar intensity", "instantaneous insolation", "insolation" or "incident radiant flux density". The use of these terms is deprecated.

**3.16 optical air mass:** Measure of the length of the path traversed by light rays from the sun through the atmosphere to sea-level, expressed with reference to the normal (vertical) path length.

**3.17 pyranometer:** Radiometer designed for measuring the irradiance on a plane receiving surface which results from the radiant fluxes incident from the hemisphere above within the wavelength range of 0,3 µm to 3 µm.

**3.18 pyrgeometer:** Instrument for determining the irradiance on a plane receiving surface which results from the radiant flux incident from the hemisphere above within the wavelength range of approximately 3 µm to 50 µm.

NOTE 3 This spectral range is similar to that of atmospheric longwave radiation and is only nominal. The spectral response of a pyrgeometer depends largely on the material used for the domes which protect each receiving surface.

**3.19 pyrheliometer:** Instrument using a collimated detector for measuring the direct (beam) radiation received from a solid angle centred on the sun's disc, on a plane perpendicular to the axis of the solid angle.

The output of the instrument can be read as either irradiance or irradiation.

NOTE 4 The spectral response of a pyrheliometer should be approximately constant in the wavelength range of 0,3 µm to 3 µm, and its acceptance angle should be less than 6°. It is synonymous with the deprecated term "actinometer".

**3.20 radiant energy:** Energy emitted, transferred or received as radiation.

**3.21 radiant energy flux:** Power emitted, transferred or received as radiation.

**3.22 radiation:** Phenomenon of energy transfer in the form of electromagnetic waves.

**3.23 radiometer:** Instrument used for measuring radiation.

The output of the instrument can be read as either irradiance or irradiation.

**3.24 solar irradiance simulator:** Artificial source of radiant energy simulating solar radiation, usually an electric lamp or an array of such lamps.

**3.25 solar thermal collector:** Device designed to absorb solar radiation and to transfer the thermal energy so gained to a fluid passing through it.

NOTE 5 Sometimes called "panel", the use of which is deprecated to avoid potential confusion with photovoltaic panels.

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**3.26 time constant:** Time required for a system whose performance can be approximated by a first-order differential equation, to have its output changed by 63,22 % of its final change in output following a step change in input.

# 4 Symbols and units

The symbols and their units used in this part of ISO 9806 are given in annex A.

# 5 Collector mounting and location

## 5.1 General

The way in which a collector is mounted will influence the results of thermal performance tests. Collectors tested in accordance with this part of ISO 9806 shall therefore be mounted in accordance with 5.2 to 5.8.

Full-size collector modules shall be tested, because the edge losses of small collectors may significantly reduce their overall performance.

## 5.2 Collector mounting frame

The collector mounting frame shall in no way obstruct the aperture of the collector, and shall not significantly affect the back or side insulation. Unless otherwise specified (for example, when the collector is part of an integrated roof array), an open mounting structure shall be used which allows air to circulate freely around the front and back of the collector. The collector shall be mounted such that the lower edge is not less than 0,5 m above the local ground surface.

Currents of warm air, such as those which rise up the walls of a building, shall not be allowed to pass over the collector. Where collectors are tested on the roof of a building, they shall be located at least 2 m away from the roof edge.

## 5.3 Tilt angle

In order to facilitate international comparisons of test results, the collector shall be mounted such that the angle of tilt of the aperture from the horizontal is:

latitude $\pm$ 5° but not less than 30°.

Collectors may be tested at other tilt angles, as recommended by manufacturers or specified for actual installations.

NOTE 6 For many collectors, the influence of tilt angle is small, but it can be an important variable for specialized collectors such as those incorporating heat pipes.

## 5.4 Collector orientation

The collector may be mounted outdoors in a fixed position facing the equator, but this will result in the time available for testing being restricted by the acceptance range of incidence angles. A more versatile approach is to move the collector to follow the sun in azimuth, using manual or automatic tracking.

## 5.5 Shading from direct solar irradiance

The location of the test stand shall be such that no shadow is cast on the collector during the test.

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## 5.6 Diffuse and reflected solar irradiance

For the purposes of analysis of outdoor test results, solar irradiance not coming directly from the sun's disc is assumed to come isotropically from the hemispherical field of view of the collector. In order to minimize the errors resulting from this approximation, the collector shall be located where there will be no significant solar radiation reflected onto it from surrounding buildings or surfaces during the tests, and where there will be no significant obstructions in the field of view. With some collector types, such as evacuated tubular collectors, it may be equally important to minimize reflections on both the back and the front fields of view. Not more than 5 % of the collector's field of view shall be obstructed, and it is particularly important to avoid buildings or large obstructions subtending an angle of greater than approximately 15° with the horizontal in front of the collectors.

The reflectance of most rough surfaces such as grass, weathered concrete or chippings is not usually high enough to cause problems during collector testing. Surfaces to be avoided in the collector's field of view include large expanses of glass, metal or water.

In most solar simulators the simulated beam approximates direct solar irradiance only. In order to simplify the measurement of simulated irradiance, it is necessary to minimize reflected irradiance. This can be achieved by painting all surfaces in the test chamber with a dark (low reflectance) paint.

## 5.7 Thermal irradiance

The performance of some collectors is particularly sensitive to the levels of thermal irradiance.

The temperature of surfaces adjacent to the collector shall be as close as possible to that of the ambient air in order to minimize the influence of thermal radiation. For example, the outdoor field of view of the collector should not include chimneys, cooling towers or hot exhausts.

For indoor and simulator testing, the collector shall be shielded from hot surfaces such as radiators, air-conditioning ducts and machinery, and from cold surfaces such as windows and external walls. Shielding is important both in front of and behind the collector.

## 5.8 Wind

The performance of many collectors is sensitive to air speeds. In order to maximize the reproducibility of results, collectors shall be mounted such that air can freely pass over the aperture, back and sides of the collector. The mean wind speed, parallel to the collector aperture, should be between the limits specified in 8.3. Where necessary, artificial wind generators shall be used to achieve these wind speeds.

Collectors designed for integration into a roof may have their backs protected from the wind; if so, this shall be reported with the test results.

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# 6 Instrumentation

## 6.1 Solar radiation measurement

### 6.1.1 Pyranometer

A class I (according to ISO 9060) pyranometer shall be used to measure the global short-wave radiation from both the sun and the sky. The recommended practice for use given in ISO/TR 9901 should be observed.

#### 6.1.1.1 Precautions for effects of temperature gradient

The pyranometer used during the test(s) shall be placed in a typical test position and allowed to equilibrate for at least 30 min before data-taking commences.

#### 6.1.1.2 Precautions for effects of humidity and moisture

The pyranometer shall be provided with a means of preventing accumulation of moisture that may condense on surfaces within the instrument and affect its reading. An instrument with a desiccator that can be inspected is required. The condition of the desiccator shall be observed prior to and following each daily measurement sequence.

#### 6.1.1.3 Precautions for infrared radiation effects on pyranometer accuracy

Pyranometers used to measure the irradiance of the solar irradiance simulator shall be mounted in such a way as to minimize the effects on its readings of the infrared radiation of wavelength above 3 µm from the simulator light source.

#### 6.1.1.4 Mounting of pyranometers outdoors

The pyranometer shall be mounted such that its sensor is coplanar, within a tolerance of ± 1°, with the plane of the collector aperture. It shall not cast a shadow onto the collector aperture at any time during the test period. The pyranometer shall be mounted so as to receive the same levels of direct, diffuse and reflected solar radiation as are received by the collector.

For outdoor testing, the pyranometer shall be mounted at the midheight of the collector. The body of the pyranometer and the emerging leads of the connector shall be shielded to minimize solar heating of the electrical connections. Care shall also be taken to minimize energy reflected and reradiated from the solar collector onto the pyranometer.

#### 6.1.1.5 Use of pyranometers in solar irradiance simulators

Pyranometers may be used to measure both the distribution of simulated solar irradiance over the collector aperture and the variation in simulated irradiance with time (see 9.6.1). The pyranometers shall be mounted and protected as for outdoor testing. Alternatively, other types of radiation detector may be used, provided that they have been calibrated for simulated solar radiation.

#### 6.1.1.6 Calibration interval

Pyranometers shall be calibrated for solar response within 12 months preceding the collector test(s) in accordance with the procedure given in ISO 9846 or ISO 9847. Any change of more than ± 1 % over a year period shall warrant the use of more frequent calibration or replacement of the instrument. If the instrument is damaged in any significant manner, it shall be recalibrated or replaced. All calibrations shall be performed with respect to the world radiometric reference (WRR) scale.

### 6.1.2 Measurement of the angle of incidence of direct solar radiation

A simple device for measuring the angle of incidence of direct solar radiation can be produced by mounting a pointer normal to a flat plate on which graduated concentric rings are marked. The length of the shadow cast by the pointer may be measured using the concentric rings and used to determine the angle of incidence. The device should be positioned in the collector plane and to one side of the collector.

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NOTE 7 The angle of incidence of direct solar radiation ($\theta$) may be calculated from the solar hour angle ($\omega$), the collector tilt angle ($\beta$), the collector azimuth angle ($\gamma$) and the latitude of the test site ($\phi$), using the following relations:

$$\cos\theta = (\sin\delta \sin\phi \cos\beta) - (\sin\delta \cos\phi \sin\beta \cos\gamma) + (\cos\delta \cos\phi \cos\beta \cos\omega) + (\cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega) + (\cos\delta \sin\beta \sin\gamma \sin\omega)$$

where the solar declination $\delta$ for day number $n$ of the year is given by:

$$\delta = 23{,}45 \sin [360(284 + n)/365]$$

## 6.2 Thermal radiation measurement

### 6.2.1 Measurement of thermal irradiance outdoors

The variations of thermal irradiance outdoors are not normally taken into account for collector testing. However, a pyrgeometer may be mounted in the plane of the collector aperture and to one side at midheight, to determine the thermal irradiance at the collector aperture.

### 6.2.2 Determination of thermal irradiance indoors and in solar simulators

#### 6.2.2.1 Measurement

The thermal irradiance may be measured using a pyrgeometer as indicated in 6.2.1 for outdoor measurements. Pyrgeometers should be well ventilated in order to minimize the influence of solar or simulated solar irradiance.

For indoor testing, the thermal irradiance shall be determined with an accuracy of $\pm$ 10 W/m$^2$.

#### 6.2.2.2 Calculation

Provided that all sources and sinks of thermal radiation in the field of view of the collector can be identified, the thermal irradiance at the collector aperture may be calculated using temperature measurements, surface emittance measurements and radiation view factors.

The thermal irradiance incident on a collector surface (designated 1), from a hotter surface (designated 2) is given by $\sigma\varepsilon_2 F_{12} T_2^4$.

Or, more usefully, the additional thermal irradiance (compared with that which would be present if surface 2 had been a perfect black body at ambient temperature) is given by:

$$\sigma F_{12} (\varepsilon_2 T_2^4 - T_a^4) \quad \ldots (1)$$

See annex A, clause A.1 for explanation of symbols. Radiation view factors are given in textbooks on radiation heat transfer.

The thermal irradiance at the collector aperture may also be calculated from a series of measurements made for small solid angles in the field of view. Such measurements can be made using a pyrheliometer with and without a glass filter to identify the thermal component of the total irradiance.

## 6.3 Temperature measurements

Three temperature measurements are required for solar collector testing. These are the fluid temperature at the collector inlet, the fluid temperature at the collector outlet, and the ambient air temperature. The required accuracy and the environment for these measurements differ, and hence the transducer and associated equipment may be different.

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### 6.3.1 Measurement of heat transfer fluid inlet temperature ($t_{in}$)

#### 6.3.1.1 Required accuracy

The temperature of the heat transfer fluid at the collector inlet shall be measured to an accuracy of ± 0,1 °C, but in order to check that the temperature is not drifting with time, a very much better resolution of the temperature signal to ± 0,02 °C is required.

NOTE 8 This resolution is needed for all temperatures used for collector testing (i.e. over the range 0 °C to 100 °C) which is a particularly demanding accuracy for recording by data logger, as it requires a resolution of one part in 4 000 or a 12-bit digital system.

#### 6.3.1.2 Mounting of sensors

The transducer for temperature measurement shall be mounted at no more than 200 mm from the collector inlet, and insulation shall be placed around the pipework both upstream and downstream of the transducer. If it is necessary to position the transducer more than 200 mm away from the collector, then a test shall be made to verify that the measurement of fluid temperature is not affected.

To ensure mixing of the fluid at the position of temperature measurement, a bend in the pipework, an orifice or a fluid-mixing device shall be placed upstream of the transducer, and the transducer probe shall point upstream and in a pipe where the flow is rising (to prevent air from being trapped near the sensor), as shown in figure 1.

### 6.3.2 Determination of heat transfer fluid temperature difference ($\Delta T$)

The difference between the collector outlet and inlet temperatures ($\Delta T$) shall be determined to an accuracy of ± 0,1 K. Accuracies approaching ± 0,02 K can be achieved with modern well-matched and calibrated transducers, and hence it is possible to measure heat transfer fluid temperature differences of 1 K or 2 K with a reasonable accuracy.

Dimensions in millimetres

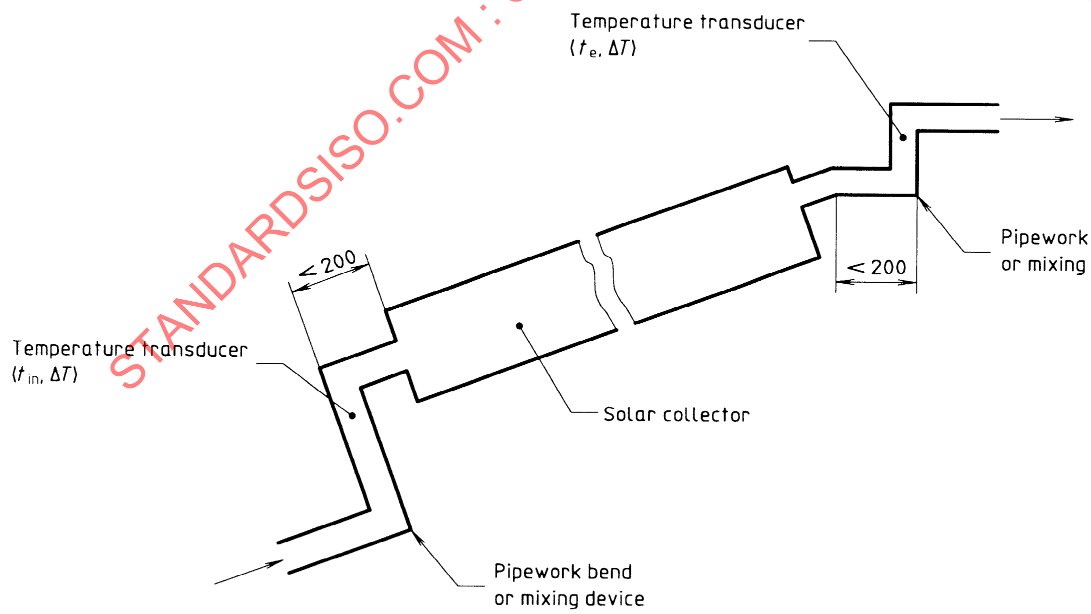


**Figure 1 — Recommended transducer positions for measuring the heat transfer fluid inlet and outlet temperatures**

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### 6.3.3 Measurement of surrounding air temperature ($t_a$)

#### 6.3.3.1 Required accuracy

The ambient or surrounding air temperature shall be measured to an accuracy of ± 0,50 °C.

#### 6.3.3.2 Mounting of sensors

For outdoor measurements the transducer shall be shaded from direct and reflected solar radiation by means of a white-painted, well-ventilated shelter, preferably with forced ventilation. The shelter itself shall be shaded and placed at the midheight of the collector but at least 1 m above the local ground surface to ensure that it is removed from the influence of ground heating. The shelter shall be positioned to one side of the collector and not more than 10 m from it.

If air is forced over the collector by a wind generator, the air temperature shall be measured in the outlet of the wind generator and checks made to ensure that this temperature does not deviate from the ambient air temperature by more than ± 1 °C.

## 6.4 Measurement of collector liquid flowrate

Mass flowrates may be measured directly or, alternatively, they may be determined from measurements of volumetric flowrate and temperature.

The accuracy of the liquid flowrate measurement shall be within ± 1,0 % of the measured value, in mass per unit time.

The flowmeter shall be calibrated over the range of fluid flowrates and temperatures to be used during collector testing.

NOTE 9 The temperature of the fluid in volumetric flowmeters should be known with sufficient accuracy to ensure that mass flowrates can be determined to within the limits specified.

## 6.5 Wind velocity

The heat losses from a collector increase with increasing air speed over the collector, but the influence of wind direction is not well understood. Measurements of wind direction are therefore not used for collector testing. The relationship between the meteorological wind speed and the air speed over the collector depends on the location of the test facility, so meteorological wind speed is not a useful parameter for collector testing. By using the wind speed measured over the collector, it is possible to define clearly the conditions in which the tests were performed.

### 6.5.1 Required accuracy

The speed of the surrounding air over the front surface of the collector shall be measured to an accuracy of ± 0,5 m/s for both indoor and outdoor testing.

Under outdoor conditions the surrounding air speed is seldom constant, and gusting frequently occurs. The measurement of an average air speed is therefore required during the test period. This may be obtained either by an arithmetic average of sampled values or by a time integration over the test period.

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### 6.5.2 Mounting of sensors

During indoor testing, the air speed may vary from one end of the collector to the other. A series of air speed measurements shall therefore be taken, at a distance of 100 mm in front of the collector aperture, at equally spaced positions over the collector area. An average value shall then be determined. Air speed measurements indoors in stable conditions shall be made before and after performance test points to avoid obscuring the collector aperture.

When testing outdoors in locations where the mean wind speed lies below 3 m/s, an artificial wind generator shall be used, and anemometer measurements made in the same way as for indoor testing. In windy locations, the wind speed measurement shall be made near to the collector at the midheight of the collector. The sensor shall not be shielded from the wind and it shall not cast a shadow on the collector during test periods.

### 6.5.3 Calibration

The anemometer shall be recalibrated at yearly intervals.

## 6.6 Pressure measurements

The heat transfer fluid pressure drop across the collector shall be measured with a device having an accuracy of ± 3,5 kPa.

## 6.7 Elapsed time

Elapsed time shall be measured to an accuracy of ± 0,2 %.

## 6.8 Instrumentation/data recorders

In no case shall the smallest scale division of the instrument or instrument system exceed twice the specified accuracy. For example, if the specified accuracy is ± 0,1 °C, the smallest scale division shall not exceed 0,2 °C.

Digital techniques and electronic integrators shall have an accuracy equal to or better than ± 1,0 % of the measured value.

Analog and digital recorders shall have an accuracy equal to or better than ± 0,5 % of the full-scale reading and have a time constant of 1 s or less. The peak signal indication shall be between 50 % and 100 % of full scale.

The input impedance of recorders shall be greater than 1 000 times the impedance of the sensors or 10 MΩ, whichever is higher.

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## 6.9 Collector area

The collector area (absorber, gross or aperture) shall be measured to an accuracy of ± 0,1 %.

## 6.10 Collector fluid capacity

The fluid capacity of the collector, expressed as an equivalent mass of the heat transfer fluid used for the test, shall be measured to an accuracy of at least ± 10 %.

Measurements may be made either by weighing the collector when empty and again when filled with fluid, or by filling and emptying the collector to determine the mass of fluid which it will contain. The temperature of the fluid should be kept within 20 °C of the ambient temperature.

# 7 Test installation

## 7.1 General consideration

Examples of test configurations for testing solar collectors employing liquid as the heat transfer fluid are shown in figures 2 and 3. These are schematic only, and are not drawn to scale.

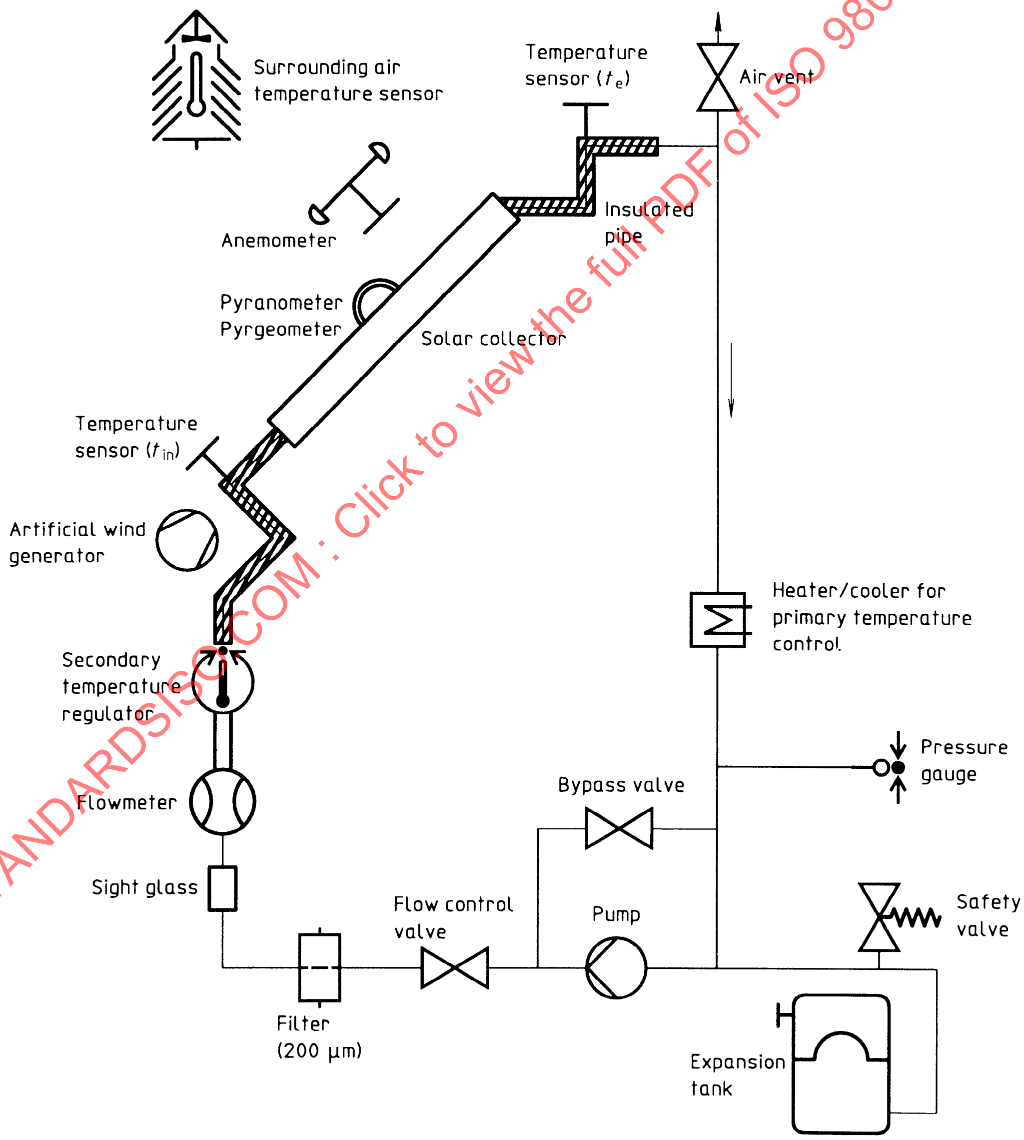


**Figure 2 — Example of a closed test loop**

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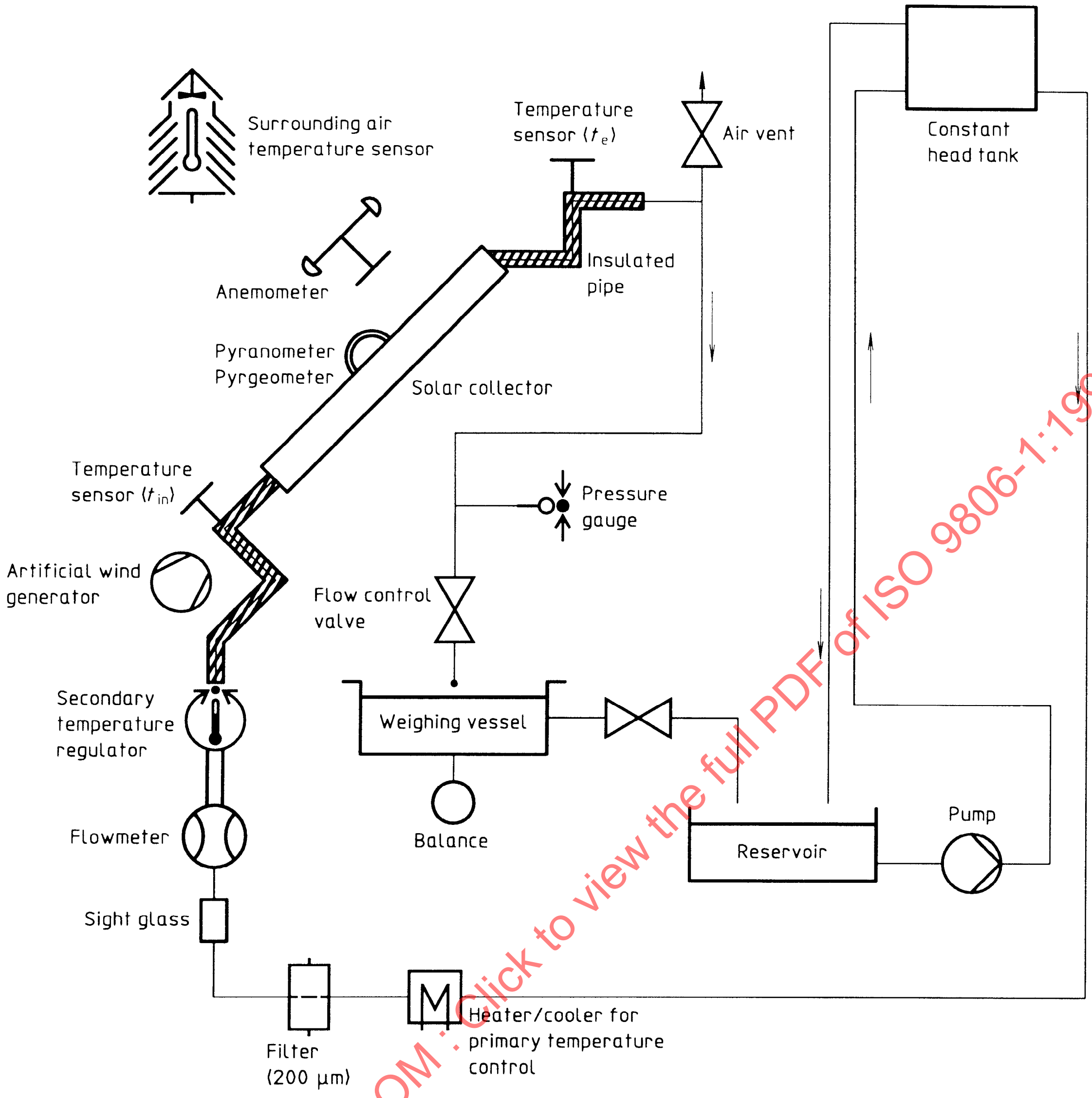


**Figure 3 — Example of an open test loop**

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## 7.2 Heat transfer fluid

The heat transfer fluid used for collector testing may be water or a fluid recommended by the collector manufacturer.

The specific heat capacity and density of the fluid used shall be known to within ± 1 % over the range of fluid temperatures used during the tests. These values are given for water in annex D. Some fluids may need to be changed periodically to ensure that their properties remain well defined.

The mass flowrate of the heat transfer fluid shall be the same throughout the test sequence used to determine the thermal efficiency curve, time constant and incident angle modifiers for a given collector.

## 7.3 Pipework and fittings

The piping used in the collector loop shall be resistant to corrosion and suitable for operation at temperatures up to 95 °C. If nonaqueous fluids are used, then compatibility with system materials shall be confirmed.

Pipe lengths shall generally be kept short. In particular, the length of piping between the outlet of the fluid temperature regulator and the inlet to the collector shall be minimized, to reduce the effects of the environment on the inlet temperature of the fluid. This section of pipe shall be insulated to ensure a rate of heat loss of less than 0,2 W/K, and shall be protected by a reflective weatherproof coating.

Pipework between the temperature sensing points and the collector (inlet and outlet) shall be protected with insulation and reflective weatherproof covers to beyond the positions of the temperature sensors, such that the calculated temperature gain or loss along either pipe portion does not exceed 0,01 K under test conditions. Flow-mixing devices such as pipe bends are required immediately upstream of temperature sensors (see 6.3).

A short length of transparent tube shall be installed in the fluid loop so that air bubbles and any other contaminants will be observed if present. The transparent tube shall be placed close to the collector inlet but shall not influence the fluid inlet temperature control or temperature measurements. A variable area flowmeter is convenient for this purpose, as it simultaneously gives an independent visual indication of the flowrate.

An air separator and air vent shall be placed at the outlet of the collector, and at other points in the system where air can accumulate.

Filters shall be placed upstream of the flow measuring device and the pump, in accordance with normal practice (a nominal filter size of 200 µm is usually adequate).

### 7.4 Pump and flow control devices

The fluid pump shall be located in the collector test loop in such a position that the heat from it which is dissipated in the fluid does not affect either the control of the collector inlet temperature or the measurements of the fluid temperature rise through the collector.

With some types of pump, a simple bypass loop and manually controlled needle valve may provide adequate flow control. Where necessary, a proprietary flow control device may be added to stabilize the mass flowrate.

The pump and flow controller shall be capable of maintaining the mass flowrate through the collector stable to within ± 1 % despite temperature variations, at any inlet temperature chosen within the operating range.

### 7.5 Temperature regulation of the heat transfer fluid

It is imperative that a collector test loop be capable of maintaining a constant collector inlet temperature at any temperature level chosen within the operating range. Since the rate of energy collection in the collector is deduced by measuring instantaneous values of the fluid inlet and outlet temperatures, it follows that small variations in inlet temperature could lead to errors in the rates of energy collection deduced. It is particularly important to avoid any drift in the collector inlet temperature.

Test loops shall therefore contain two stages of fluid inlet temperature control, as shown in figures 2 and 3. The primary temperature controller shall be placed upstream of the flowmeter and flow controller. A secondary temperature regulator shall be used to adjust the fluid temperature just before the collector inlet. This secondary regulator should normally not be used to adjust the fluid temperature by more than ± 2 K.

## 8 Outdoor steady-state efficiency test

### 8.1 Test installation

The collector shall be mounted in accordance with the recommendations given in clause 5, and coupled to a test loop as described in clause 7. The heat transfer fluid shall flow from the bottom to the top of the collector, or as recommended by the manufacturer.

### 8.2 Preconditioning of the collector

Before being tested for performance, the collector shall have undergone the sequence of qualification tests specified in ISO 9806-2.

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The collector shall be visually inspected and any damage recorded.

The collector aperture cover shall be thoroughly cleaned.

If moisture has formed on the collector components, then the heat transfer fluid shall be circulated at approximately 80 °C for as long as is necessary to dry out the insulation and collector enclosure. If this form of preconditioning is carried out, then it shall be reported with the test results.

The collector pipework shall be vented of trapped air by means of an air valve or by circulating the fluid at a high flowrate, as necessary.

The fluid shall be inspected for entrained air or particles, by means of the transparent tube built into the fluid loop pipework. Any contaminants shall be removed.

## 8.3 Test conditions

At the time of the test, the total solar irradiance at the plane of the collector aperture shall be greater than 800 W/m$^2$.

The angle of incidence of direct solar radiation at the collector aperture shall be in the range in which the incident angle modifier for the collector varies by no more than ± 2 % from its value at normal incidence. For single glazed flat plate collectors, this condition will usually be satisfied if the angle of incidence of direct solar radiation at the collector aperture is less than 30 °. However, much lower angles may be required for particular designs. In order to characterize collector performance at other angles, an incident angle modifier may be determined (see clause 11).

The average value of the surrounding air speed, taking into account spatial variations over the collector and temporal variations during the test period, shall lie between 2 m/s and 4 m/s.

Unless otherwise recommended, the fluid flowrate shall be set at approximately 0,02 kg/s per square metre of collector gross area. It shall be held stable to within ± 1 % of the set value during each test period, and shall not vary by more than ± 10 % of the set value from one test period to another.

In some collectors the recommended fluid flowrate may be close to the transition region between laminar and turbulent flow. This may cause instability of the internal heat transfer coefficient and hence variations in measurements of collector efficiency. In order to characterize such a collector in a reproducible way, it may be necessary to use a higher flowrate, but this shall be clearly stated with the test results.

Measurements of fluid temperature difference of less than 1,5 K shall not be included in the test results because of the associated problems of instrument accuracy.

## 8.4 Test procedure

The collector shall be tested over its operating temperature range under clear sky conditions in order to determine its efficiency characteristic.

Data points which satisfy the requirements given below shall be obtained for at least four fluid inlet temperatures spaced evenly over the operating temperature range of the collector. One inlet temperature shall be selected such that the mean fluid temperature in the collector lies within ± 3 K of the ambient air temperature, in order to obtain an accurate determination of $\eta_0$. (If water is the heat transfer fluid, 70 °C is usually adequate as a maximum temperature.)

At least four independent data points shall be obtained for each fluid inlet temperature, to give a total of 16 data points. If test conditions permit, an equal number of data points shall be taken before and after solar noon for each fluid inlet temperature. The latter is not required if the collectors are moved to follow the sun in azimuth and altitude using automatic tracking.

During a test, measurements shall be made as specified in 8.5. These may then be used to identify test periods from which satisfactory data points can be derived.

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## 8.5 Measurements

The following measurements shall be obtained:

a) the gross collector area $A_G$, the absorber area $A_A$ and the aperture area $A_a$;

b) the fluid capacity;

c) the global solar irradiance at the collector aperture;

d) the diffuse solar irradiance at the collector aperture;

e) the angle of incidence of direct solar radiation (alternatively, this angle may be determined by calculation);

f) the surrounding air speed;

g) the surrounding air temperature;

h) the temperature of the heat transfer fluid at the collector inlet;

i) the temperature of the heat transfer fluid at the collector outlet;

j) the flowrate of the heat transfer fluid.

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## 8.6 Test period (steady-state)

The test period for a steady-state data point shall include a preconditioning period of at least 15 min with the correct fluid measurement temperature at the inlet, followed by a steady-state measurement period of at least 15 min.

In all cases, the length of the steady-state measurement period shall be greater than four times the ratio of the effective thermal capacity $C$ of the collector to the thermal flowrate $\dot{m}c_f$ of the fluid through the collector (see clause 10 for determination of the effective thermal capacity).

A collector 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 1. To establish that a steady state exists, average values of each parameter taken over successive periods of 30 s shall be compared with the mean value over the measurement period.

**Table 1 — Permitted deviation of measured parameters during a measurement period**

| Parameter | Permitted deviation from the mean value |
|---|---|
| Test solar irradiance | $\pm$ 50 W/m$^2$ |
| Surrounding air temperature | $\pm$ 1 K |
| Fluid mass flowrate | $\pm$ 1 % |
| Fluid temperature at the collector inlet | $\pm$ 0,1 K |

## 8.7 Presentation of results

The measurements shall be collated to produce a set of data points which meet the required test conditions, including those for steady-state operation. These shall be presented using the data format sheets given in annex A.

### 8.8 Computation of collector efficiency

The instantaneous efficiency of a solar collector, $\eta$ (or $\bar{\eta}$), operating under steady-state conditions, is defined as the ratio of the actual useful power extracted to the solar energy intercepted by the collector.

The actual useful power extracted, $\dot{Q}$, is calculated from:

$$\dot{Q} = \dot{m} c_{\mathrm{f}} \Delta T \qquad \ldots (2)$$

A value of $c_{\mathrm{f}}$ corresponding to the mean fluid temperature shall be used.

If $\dot{m}$ is obtained from volumetric flowrate measurement, then the density shall be determined for the temperature of the fluid in the flowmeter.

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#### 8.8.1 Solar energy intercepted by the collector

Provided that the angle of incidence is less than 30°, the use of an incident angle modifier, as discussed in clause 11, is not required for single glazed flat plate collectors.

The solar energy intercepted by the collector is $A_{\mathrm{G}}G$ when it is referred to the gross collector area, and so

$$\eta_{\mathrm{G}} = \frac{\dot{Q}}{A_{\mathrm{G}}G} \qquad \ldots (3)$$

The solar energy intercepted is $A_{\mathrm{A}}G$ when it is referred to the absorber area of the collector, and so in this case

$$\eta_{\mathrm{A}} = \frac{\dot{Q}}{A_{\mathrm{A}}G} \qquad \ldots (4)$$

#### 8.8.2 Reduced temperature difference

The instantaneous efficiency $\eta$ (or $\bar{\eta}$) shall be presented graphically as a function of the reduced temperature difference $T^*$.

When the mean temperature of the heat transfer fluid $t_{\mathrm{m}}$ is used, where

$$t_{\mathrm{m}} = t_{\mathrm{in}} + \frac{\Delta T}{2} \qquad \ldots (5)$$

the reduced temperature difference is calculated as:

$$T_{\mathrm{m}}^* = \frac{t_{\mathrm{m}} - t_{\mathrm{a}}}{G} \qquad \ldots (6)$$

If the temperature at the collector inlet is employed, the reduced temperature difference is calculated as:

$$T_{\mathrm{i}}^* = \frac{t_{\mathrm{in}} - t_{\mathrm{a}}}{G} \qquad \ldots (7)$$

#### 8.8.3 Graphical presentation of instantaneous efficiency

Graphical presentation of $\eta$ (or $\bar{\eta}$) shall be made by statistical curve fitting, using the least squares method, to obtain an instantaneous efficiency curve of the form

$$\eta = \eta_0 - a_1 T^* - a_2 G (T^*)^2 \qquad \ldots (8)$$

or

$$\eta = \eta_0 - U T^* \qquad \ldots (9)$$

The choice between a first- or a second-order curve shall be based on the closeness of fit which can be achieved by least squares regression. A second-order fit shall not be used if the value deduced for $a_2$ is negative.

The value of $G$ to be used for the presentation of second-order fits shall be 800 W/m$^2$.

The test conditions shall be recorded on the data format sheets given in annex A.

Data points which have been measured in conditions where the diffuse solar irradiance is greater than 20 % of the total solar irradiance shall be corrected to equivalent normal irradiance conditions using the method given in annex B. Where diffuse solar irradiance is less than 20 %, its influence may be neglected. If the incident angle modifier of a collector cannot be determined with confidence, then the collector shall not be tested at diffuse irradiance levels of greater than 20 %.

The following subclauses provide expressions for the instantaneous efficiency for four cases considering combinations of collector area (gross area, absorber area) and reduced temperature difference ($T^*_m$, $T^*_i$).

Determine the coefficients of as many expressions (see 8.8.3.1 and 8.8.3.2) as is necessary. The curves should be presented according to A.3.4 to A.3.7 of annex A.

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#### 8.8.3.1 Instantaneous efficiency based on gross collector area

Employment of the reduced temperature difference $T^*_m$ provides the following two equations:

$$\bar{\eta}_G = \bar{\eta}_{0G} - \bar{U}_G \frac{t_m - t_a}{G} \qquad \ldots (10)$$

or

$$\bar{\eta}_G = \bar{\eta}_{0G} - \bar{a}_{1G} \frac{t_m - t_a}{G} - \bar{a}_{2G}\, G \left(\frac{t_m - t_a}{G}\right)^2 \qquad \ldots (11)$$

where

$$\bar{\eta}_G = \frac{\dot{Q}}{A_G\, G} \qquad \ldots (12)$$

If the reduced temperature difference $T^*_i$ is used, the equations for the instantaneous efficiency are:

$$\eta_G = \eta_{0G} - U_G \frac{t_{in} - t_a}{G} \qquad \ldots (13)$$

or

$$\eta_G = \eta_{0G} - a_{1G} \frac{t_{in} - t_a}{G} - a_{2G}\, G \left(\frac{t_{in} - t_a}{G}\right)^2 \qquad \ldots (14)$$

where

$$\eta_G = \frac{\dot{Q}}{A_G\, G} \qquad \ldots (15)$$

#### 8.8.3.2 Instantaneous efficiency based on absorber area

With reference to the reduced temperature difference $T^*_m$ the equations for instantaneous efficiency are:

$$\bar{\eta}_A = \bar{\eta}_{0A} - \bar{U}_A \frac{t_m - t_a}{G} \qquad \ldots (16)$$

or

$$\bar{\eta}_A = \bar{\eta}_{0A} - \bar{a}_{1A} \frac{t_m - t_a}{G} - \bar{a}_{2A}\, G \left( \frac{t_m - t_a}{G} \right)^2 \qquad \ldots (17)$$

where

$$\bar{\eta}_A = \frac{\dot{Q}}{A_A\, G} \qquad \ldots (18)$$

The use of the reduced temperature difference $T_i^*$ provides the following equations for instantaneous efficiency:

$$\eta_A = \eta_{0A} - U_A \frac{t_{in} - t_a}{G} \qquad \ldots (19)$$

or

$$\eta_A = \eta_{0A} - a_{1A} \frac{t_{in} - t_a}{G} - a_{2A}\, G \left( \frac{t_{in} - t_a}{G} \right)^2 \qquad \ldots (20)$$

where

$$\eta_A = \frac{\dot{Q}}{A_A\, G} \qquad \ldots (21)$$

### 8.8.4 Conversion of thermal performance test characteristics

By assuming a linear temperature rise across the collector, the flowrate $\dot{m}$ of the heat transfer fluid can be used to relate the coefficients $\bar{\eta}_{0G}$ and $\bar{U}_G$ of equation (10) to the coefficients $\eta_{0G}$ and $U_G$ of equation (13). One set of equations is:

$$\eta_{0G} = \bar{\eta}_{0G} \left[ \frac{\zeta}{\zeta + \frac{\bar{U}_G}{2}} \right] \qquad \ldots (22)$$

$$U_G = \bar{U}_G \left[ \frac{\zeta}{\zeta + \frac{\bar{U}_G}{2}} \right] \qquad \ldots (23)$$

where

$$\zeta = \frac{\dot{m}\, c_f}{A_G} \qquad \ldots (24)$$

while the other set of equations is:

$$\bar{\eta}_{0G} = \eta_{0G} \left[ \frac{\zeta}{\zeta - \frac{U_G}{2}} \right] \qquad \ldots (25)$$

$$\bar{U}_G = U_G \left[ \frac{\zeta}{\zeta - \frac{U_G}{2}} \right] \qquad \ldots (26)$$

In terms of the collector gross area and the absorber area, the basic conversion equations are:

$$\bar{\eta}_A = \bar{\eta}_G \frac{A_G}{A_A} \qquad \ldots (27)$$

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$$\eta_A = \eta_G \frac{A_G}{A_A} \quad \ldots (28)$$

The use of these two equations leads to the following:

$$\bar{\eta}_{0A} = \bar{\eta}_{0G} \frac{A_G}{A_A} \quad \ldots (29)$$

$$\bar{U}_A = \bar{U}_G \frac{A_G}{A_A} \quad \ldots (30)$$

$$\bar{a}_{1A} = \bar{a}_{1G} \frac{A_G}{A_A} \quad \ldots (31)$$

$$\bar{a}_{2A} = \bar{a}_{2G} \frac{A_G}{A_A} \quad \ldots (32)$$

and also to:

$$\eta_{0A} = \eta_{0G} \frac{A_G}{A_A} \quad \ldots (33)$$

$$U_A = U_G \frac{A_G}{A_A} \quad \ldots (34)$$

$$a_{1A} = a_{1G} \frac{A_G}{A_A} \quad \ldots (35)$$

$$a_{2A} = a_{2G} \frac{A_G}{A_A} \quad \ldots (36)$$

## 9 Steady-state efficiency test using a solar irradiance simulator

### 9.1 General

The performance of most collectors is better in direct solar radiation than in diffuse and at present there is little experience with diffuse solar simulation. This test method is therefore designed for use only in simulators where a near-normal incidence beam of simulated solar radiation can be directed at the collector. In practice it is difficult to produce a uniform beam of simulated solar radiation and a mean irradiance level has therefore to be measured over the collector aperture.

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### 9.2 The solar irradiance simulator for steady-state efficiency testing

A simulator for steady-state efficiency testing shall have the following characteristics:

The lamps shall be capable of producing a mean irradiance over the collector aperture of at least 800 W/m$^2$. Values in the range 300 W/m$^2$ to 1 000 W/m$^2$ may also be used for specialized tests, provided that the accuracy requirements given in table 1 can be achieved and the irradiance values are noted in the test report.

The mean irradiance over the collector aperture shall not vary by more than $\pm$ 50 W/m$^2$ during a test period.

At any time the irradiance at a point on the collector aperture shall not differ from the mean irradiance over the aperture by more than $\pm$ 15 %.

The spectral distribution of the simulated solar radiation shall be approximately equivalent to that of the solar spectrum at air mass 1,5 (see annex C).

Where collectors contain spectrally selective absorbers or covers, a check shall be made to establish the effect of the difference in spectrum on the $(\tau\alpha)$ product for the collector. If the effective values of $(\tau\alpha)$ under the simulator and under the air mass 1,5 solar radiation spectrum (see annex C) differ by more than ± 1 %, then a correction shall be applied to the test results.

$$\text{Effective } (\tau\alpha) = \frac{\int_{0,3\ \mu m}^{3\ \mu m} \tau(\lambda)\ \alpha(\lambda)\ G(\lambda)\ d\lambda}{\int_{0,3\ \mu m}^{3\ \mu m} G(\lambda)\ d\lambda}$$

Measurement of the solar simulator's spectral qualities shall be in the plane of the collector over the wavelength range of (0,3 – 3) µm and shall be determined in bandwidths of 0,1 µm or smaller.

For certain lamp types, i.e. metal halide designs, it is recommended that the initial spectral determination be performed after the lamps have completed their burn-in period. The amount of infrared thermal energy (that above 4 µm) at the collector plane shall be suitably measured and reported (see 6.2).

The thermal irradiance at the collector shall not exceed that of a blackbody cavity at ambient air temperature by more than 50 $W/m^2$.

The collimation of the simulator shall be such that the angles of incidence of at least 80 % of the simulated solar irradiance lie in the range in which the incident angle modifier of the collector varies by no more than ± 2 % from its value at normal incidence. For typical flat plate collectors, this condition usually will be satisfied if at least 80 % of the simulated solar radiation received at any point on the collector under test shall have emanated from a region of the solar irradiance simulator contained within a subtended angle of 60° or less when viewed from the point.

NOTE 10 Additional requirements concerning collimation apply to measurement of the incident angle modifier (see 11.2).

The irradiance shall be monitored during the test and shall not vary by more than 3 % during the test period. The method used for measuring the irradiance during the test period shall produce values of mean irradiance which agree with those determined by spatial integration to within ± 1 %.

## 9.3 Test installation

Clause 5 describes collector mounting and location requirements.

The collector tilt angle shall be such as to receive a near-normal incidence beam of simulated solar radiation. The tilt angle shall be at or corrected to (45 ± 5)°, or as recommended by the manufacturer. Non-standard tilt angles require a simulator array that has freedom of tilt to maintain normal incidence.

A wind generator shall be used with a solar simulator to produce an air flow in accordance with 5.8.

## 9.4 Preconditioning of the collector

The procedure outlined in 8.2 shall be followed.

## 9.5 Test procedure

The collector shall be tested over its operating temperature range in approximately the same way as specified for outdoor testing (see 8.4).

However, eight test points shall be adequate for testing in solar simulators provided that at least four different inlet temperatures are used, that adequate time is allowed for temperatures to stabilize and that one inlet temperature lies within 3 K of the ambient air temperature.

During a test, measurements shall be made as specified in 9.6. These may then be used to identify test periods from which satisfactory data points can be derived.

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## 9.6 Measurements during tests in solar irradiance simulators

Measurements shall be made as specified in clause 8.

### 9.6.1 Measurement of simulated solar irradiance

NOTE 11 Simulated solar irradiance usually varies spatially over the collector aperture as well as varying with time during a test. It is therefore necessary to employ a procedure for integrating the irradiance over the collector aperture. Time variations in irradiance are usually caused by fluctuations in the electricity supply and changes in lamp output with temperature and running time. Some lamps take more than 30 min to reach a stable working condition when warming up from cold.

Pyranometers may be used to measure the irradiance of simulated solar radiation in accordance with 6.1. Alternatively, other types of radiation detector may be used, provided they have been calibrated for simulated solar radiation. Details of the instruments and the methods used to calibrate them shall be reported with the test results.

The distribution of irradiance over the collector aperture shall be measured using a grid of maximum spacing 150 mm, and the spatial mean deduced by simple averaging.

### 9.6.2 Measurement of thermal irradiance in simulators

The thermal irradiance in a solar simulator is likely to be higher than that which typically occurs outdoors. It shall therefore be measured to ensure that it does not exceed the limit given in 9.8.

The mean thermal irradiance in the collector test plane shall be determined whenever changes are made in the simulator which could affect the thermal irradiance, and at least annually. The mean thermal irradiance in the collector test plane and the date when it was last measured shall be reported with collector test results.

### 9.6.3 Ambient air temperature in simulators

Careful consideration shall be given to the measurement of $t_a$ in simulators. A mean of several measured values may be necessary. Transducers shall be shielded in order to minimize radiation exchange. The air temperature in the outlet of the wind generator shall be used for the calculations of collector performance.

## 9.7 Test period

The test period may be determined in the same way as for outdoor steady-state testing.

The more stable environment of an indoor test facility may allow steady-state conditions to be maintained more easily than outdoors, but adequate time shall still be allowed to ensure proper steady-state operation of the collector as discussed in 8.6.

## 9.8 Test conditions

The test conditions described in 8.3 for outdoor testing shall be observed with the following additions:

The thermal irradiance in the plane of the collector aperture shall not exceed that from a blackbody cavity at ambient air temperature by more than 50 W/m$^2$.

The air issuing from the wind generator shall not differ in temperature from ambient air by more than $\pm$ 1 K.

## 9.9 Computation and presentation of results

The analysis presented in 8.8 for outdoor testing is also applicable to solar simulator tests, and the results shall be presented on the format sheets shown in annex A.

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## 10 Determination of the effective thermal capacity and the time constant of a collector

### 10.1 General

The effective thermal capacity and the time constant of a collector are important parameters which determine its transient performance.

A collector can usually be considered as a combination of masses, each at a different temperature. When a collector is operating, each collector component responds differently to a change in operating conditions, so it is useful to consider an effective thermal capacity for the whole collector.

Unfortunately, the effective thermal capacity depends on the operating conditions and is not a collector parameter with a unique value. Several different test methods have been used to measure or calculate the effective thermal capacity of collectors and it has been shown that similar results can be obtained by using quite different methods. The method below is recommended because of its simplicity. An alternative, which requires only conventional collector testing facilities, does not use time derivatives (which are inherently difficult to obtain accurately) and has been shown to give reproducible results is given in annex E.

Just as there is no unique value of effective thermal capacity, there is no unique overall time constant for a collector. For most collectors, the dominant influence on the response time is the fluid transit time, and hence the first-order response varies with the fluid flowrate. Other collector components respond with different times to give an effective overall time constant which depends on the operating conditions.

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### 10.2 Determination of thermal capacity

The thermal capacity of the collector $C$ (expressed as joules per kelvin) is calculated as the sum, for each constituent element of the collector (glass, absorber, liquid contained, insulation), of the product of its mass $m_i$ (expressed in kilograms), its specific heat $c_i$ (expressed as joules per kilogram kelvin) and a weighting factor $p_i$:

$$C = \sum_i p_i \, m_i \, c_i$$

The weighting factor $p_i$ (between 0 and 1) allows for the fact that certain elements are only partially involved in collector thermal inertia.

The values of $p_i$ are given in table 2.

**Table 2 — Values of weighting factors $p_i$**

| **Elements** | $p_i$ |
|---|---|
| Absorber | 1 |
| Insulation | 0,5 |
| Heat transfer liquid | 1 |
| External glazing | 0,01 $a_1$ |
| Second glazing | 0,20 $a_1$ |
| Third glazing | 0,35 $a_1$ |

NOTE — $a_1$ denotes the second parameter of the instantaneous efficiency expression or heat loss coefficient. Where its exact value is unknown, the following approximate values should be used to determine $p_i$:

7,5 (single glazing);

4 (double glazing);

2,5 (triple glazing).

Thermal capacity can also be measured by applying the procedures described in annex E.

### 10.3 Test procedure for collector time constant

Testing shall be performed either outdoors or in a solar irradiance simulator. In either case, the solar irradiance on the plane of the collector aperture shall be greater than 800 $W/m^2$.

The heat transfer fluid shall be circulated through the collector at the same flowrate as that used during collector thermal efficiency tests.

The aperture of the collector shall be shielded from the solar radiation by means of a solar-reflecting cover, and the temperature of the heat transfer fluid at the collector inlet shall be set approximately equal to the ambient air temperature.

When a steady state has been reached, the cover shall be removed and measurements continued until steady-state conditions have been achieved again. For the purpose of this test, a steady-state condition is assumed to exist when the outlet temperature of the fluid varies by less than 0,05 °C per minute.

The following quantities shall be measured in accordance with clause 6:

a) Collector fluid inlet temperature ($t_{in}$);

b) Collector fluid outlet temperature ($t_e$);

c) Surrounding air temperature ($t_a$).

### 10.4 Calculation of collector time constant

The difference between the temperature of the fluid at the collector outlet and that of the surrounding air ($t_e - t_a$) shall be plotted against time, beginning with the initial steady-state condition $(t_e - t_a)_0$ and continuing until the second steady state has been achieved at a higher temperature $(t_e - t_a)_2$ (see figure 4).

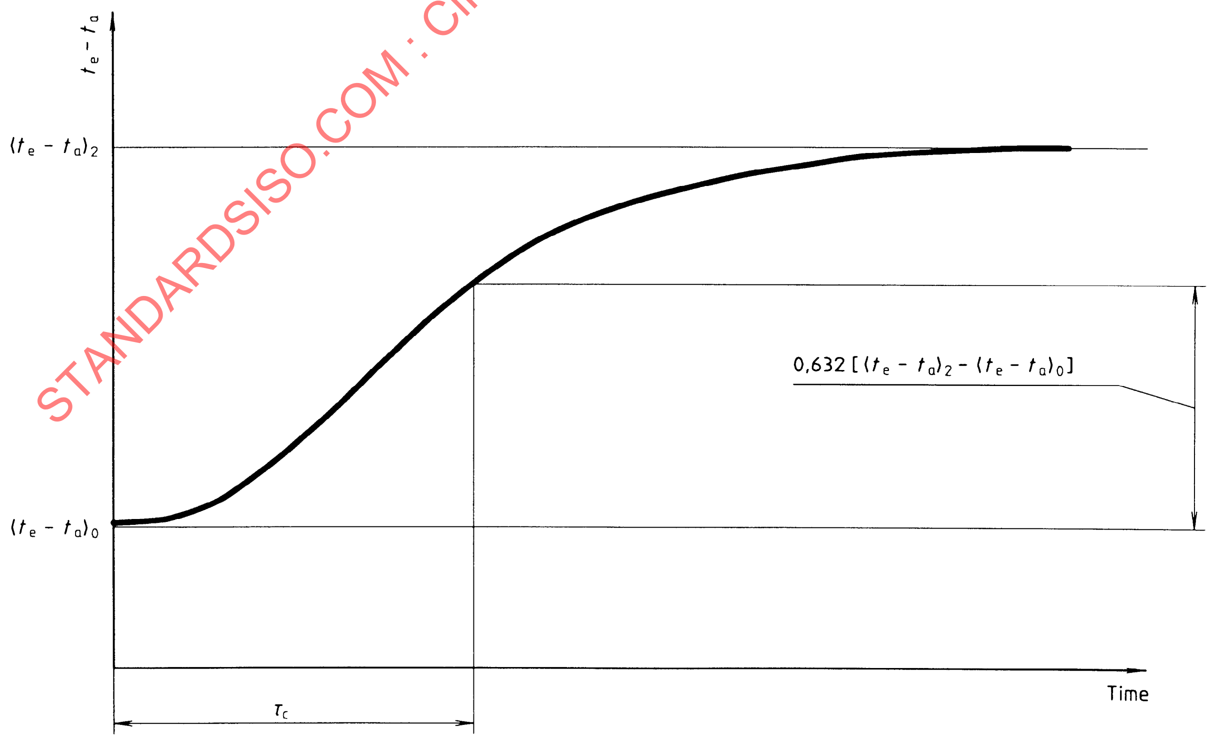


**Figure 4 — Collector time constant**

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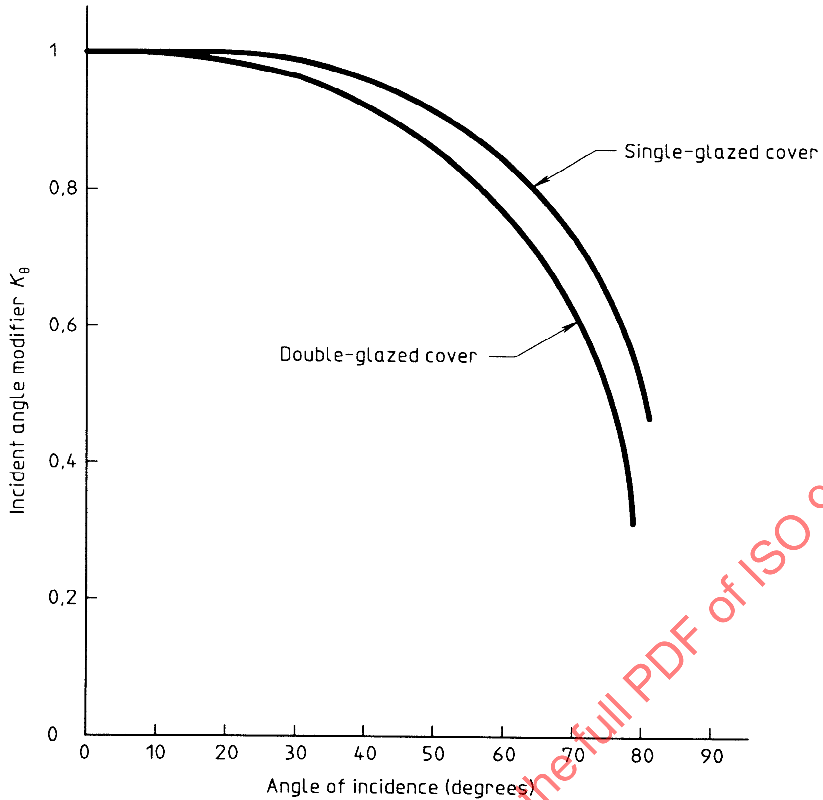


**Figure 5 — Typical incident angle modifiers $K_\theta$**

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The time constant $\tau_c$ of the collector is defined as the time taken for the collector outlet temperature to rise by 63,2 % of the total increase from $(t_e - t_a)_0$ to $(t_e - t_a)_2$ following the step increase in solar irradiance at time zero. If the response time of the temperature sensors is significant when compared with that measured for the collector, then it shall be taken into account in calculating the test results.

## 11 Collector incident angle modifier

### 11.1 General

The effective transmittance-absorptance product $(\tau\alpha)_e$ can be replaced by the value at normal incidence $(\tau\alpha)_{en}$ provided that another factor called the incident angle modifier, $K_\theta$, is introduced in equation

$$\bar{\eta}_G = F' K_\theta (\tau\alpha)_{en} - \bar{U}_G \frac{t_m - t_a}{G} \qquad \ldots (37)$$

Hence, for flat plate collectors:

$$(\tau\alpha)_e = K_\theta (\tau\alpha)_{en} \qquad \ldots (38)$$

Figure 5 shows the variation of $K_\theta$ with angle of incidence for two solar collectors.

The significance of the incident angle modifier to the test procedures outlined in this part of ISO 9806 is that the thermal efficiency values are determined for the collector at or near normal incidence conditions. Therefore, the $y$ intercept $\bar{\eta}_G$ of the efficiency curve is equal to $F' (\tau\alpha)_{en}$, for a flat plate collector. A separate measurement is conducted to determine the value of $K_\theta$ so that the performance of the collector can be predicted under a wide range of conditions and/or time of day using equation (37).

NOTE 12 The equations included in this subclause are presented in terms of $t_m$ and $A_G$. They may also be presented using $t_{in}$ and/or $A_A$. Ways of converting from one form to another are given in 8.8.4.

## 11.2 Solar irradiance simulator for the measurement of incident angle modifiers

For the measurement of the incident angle modifier, only solar irradiance simulators with the following collimation specification shall be used.

The collimation shall be such that at least 90 % of the simulated solar irradiance at any point on the collector under test has emanated from a region of the solar irradiance simulator contained within a subtended angle of 20° or less when viewed from the point.

## 11.3 Test procedures

The testing of the solar collector to determine its incident angle modifier can be done by one of two methods. However, during each test period, the orientation of the collector shall be such that the collector is maintained within ± 2,5° of the angle of incidence for which the test is being conducted.

For those collectors (e.g. evacuated tube collectors) for which the angle of incidence effects are not symmetrical with direction of incidence, it will be necessary to measure the incident angle effects from more than one direction, as discussed in annex F.

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### 11.3.1 Method 1

This method is applicable for testing indoors using a solar simulator with the characteristics specified in 9.2, or outdoors using a movable test rack (altazimuth collector mount) so that the orientation of the collector can be arbitrarily adjusted with respect to the direction of the incident solar radiation.

The collector is orientated so that the test angles of incidence between it and the direct solar radiation for the four test conditions are, respectively, approximately 0°, 30°, 45° and 60°. It is recommended that these data be taken during a single day. For some collectors with unusual optical performance characteristics, other angles of incidence will be more appropriate.

For each data point, the inlet temperature of the heat transfer fluid shall be controlled as closely as possible (preferably within ± 1 °C) to the ambient air temperature. The four separate efficiency values are determined in accordance with 8.4.

### 11.3.2 Method 2

This method is applicable for testing outdoors using a stationary test rack on which the collector orientation cannot be arbitrarily adjusted with respect to direction for incident solar radiation (except for adjustments in tilt).

For each data point, the inlet temperature of the heat transfer fluid shall be controlled, if possible, to within ± 1 °C of the ambient air temperature. The efficiency values are determined in pairs, where each pair includes one value of efficiency before solar noon and a second value after solar noon. The average incident angle between the collector and the solar beam for both data points is the same. The efficiency of the collector for the specific incident angle shall be considered equal to the average of the two values.

Efficiency values are determined in general accordance with the method described in 8.4. As with Method 1, data shall be collected for angles of incidence of approximately 0°, 30°, 45° and 60°. For some collectors with unusual optical performance characteristics, other angles of incidence may be necessary.

NOTE 13 More experience is required to confirm whether this method is applicable to special geometries, such as evacuated tubular collectors.

## 11.4 Calculation of collector incident angle modifier

Regardless of which experimental method in 11.3 is used, values for the thermal efficiency of the collector shall be determined for each value of angle of incidence. For conventional flat plate collectors, only four angles of incidence are needed, i.e. 0°, 30°, 45° and 60°. (It is noted that a rating standard using this test method may require that $K_\theta$ be measured for a different set of angles of incidence.) The inlet fluid temperature is held very close to the ambient air temperature so that $(t_{in} - t_a) \approx 0$. The relationship between $K_\theta$ and the efficiency is:

$$K_\theta = \frac{\eta_G}{F_R\,(\tau\alpha)_{en}} \qquad \ldots (39)$$

Since $F'(\tau\alpha)_{en}$ will have already been obtained as the $y$-axis intercept of the efficiency curve, values of $K_\theta$ can be computed for the different angles of incidence (see 11.3).

If the inlet fluid temperature cannot be controlled to equal the ambient air temperature within ± 1 °C, an estimate of $U_L$ should be made for the collector for the conditions of the test, and each value of $K_\theta$ computed as:

$$K_\theta = \frac{\eta_G + F_R\left(\dfrac{t_{in} - t_a}{G}\right)}{F_R\,(\tau\alpha)_{en}} \qquad \ldots (40)$$

Alternatively, each data point can be plotted on the same graph with the efficiency curve determined in accordance with clause 8 or 9, and a curve drawn through each point parallel to the efficiency curve and made to intersect the $y$ axis. The values of the $y$ intercept are the efficiency values that would have resulted had the inlet fluid temperature been controlled to equal ambient air temperature. Therefore, these values can be used in conjunction with equation (40) to compute the different values of $K_\theta$.

## 12 Determination of the pressure drop across a collector

### 12.1 General

The pressure drop across a collector may be of importance to designers of solar collector systems. The fluid normally used in the collector shall be employed for the test.

In order that a representative range of pressure drops can be determined, a number of different fluid flowrates shall be used.

### 12.2 Test installation

The collector shall be mounted in accordance with the recommendations of clause 5 and coupled to a test loop which conforms broadly with the recommendations of clause 7, although less instrumentation is required for pressure drop determination than for collector efficiency testing. The heat transfer fluid shall flow from the bottom to the top of the collector, and particular attention shall be paid to the selection of appropriate pipe fittings at the collector entry and exit ports, as discussed in 7.3.

### 12.3 Preconditioning of the collector

The fluid shall be inspected to ensure that it is clean.

The collector shall be vented of air by means of an air bleed valve or other suitable means, such as increasing the fluid flowrate for a short period to force air from the collector.

### 12.4 Test procedure

The pressure drop between the collector inlet and outlet connections shall be determined for flowrates which span the range likely to be used in a solar heating system.

In the absence of specific flowrate recommendations by the collector supplier, pressure drop measurements shall be made over the range of flowrates from 0,005 kg/s to 0,03 kg/s per square metre of collector area.

At least five measurements shall be made at values equally spaced over the flowrate range.

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### 12.5 Measurements

The following measurements shall be obtained in accordance with the recommendations given in clause 6:

a) the fluid temperature at the collector inlet;

b) the fluid flowrate;

c) the heat transfer fluid pressure drop between the collector inlet and outlet connections.

### 12.6 Pressure drop caused by fittings

The fittings used to measure the fluid pressure may themselves cause a drop in pressure. A zero check on the pressure drop shall be made by removing the collector from the fluid loop and repeating the tests with the pressure-measuring fittings directly connected together.

### 12.7 Test conditions

The fluid flowrate shall be held constant to within ± 1 % of the nominal value during test measurements.

The inlet temperature of the heat transfer fluid shall be held constant to within ± 5 °C during test measurements. The test shall be carried out with the collector at a temperature which lies within ± 10 °C of that of the surrounding air. Pressure drop tests at other temperatures may be important for oil-based heat transfer fluids.

### 12.8 Calculation and presentation of results

The pressure drop shall be presented graphically as a function of the fluid flowrate for each of the tests performed, using the format sheets given in annex A.

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# Annex A
(normative)

# Format sheets for test data

## A.1 Symbols and units

| Symbol | Meaning | Units |
|---|---|---|
| $a_1$ | algebraic constant, reference to $T_i^*$ | W/(m² K) |
| $\bar{a}_1$ | algebraic constant, reference to $T_m^*$ | W/(m² K) |
| $a_2$ | algebraic constant, reference to $T_i^*$ | W/(m² K²) |
| $\bar{a}_2$ | algebraic constant, reference to $T_m^*$ | W/(m² K²) |
| $A_A$ | absorber area of collector | m² |
| $A_a$ | aperture area of collector | m² |
| $A_G$ | gross area of collector | m² |
| AM | air mass | — |
| D | date | YYMMDD |
| $c_f$ | specific heat capacity of heat transfer fluid | J/(kg K) |
| $C$ | effective thermal capacity of collector | J/K |
| $F$ | radiation view factor | — |
| $F'$ | collector efficiency factor | — |
| $F_R$ | collector heat removal factor | — |
| $G$ 1) | global solar irradiance | W/m² |
| $G'_n$ | equivalent normal solar irradiance | W/m² |
| $G_b$ | direct solar irradiance (beam irradiance) | W/m² |
| $G_d$ | diffuse solar irradiance | W/m² |
| $E_L$ | longwave irradiance ($\lambda > 3$ µm) | W/m² |
| LT | local time | h |
| $K_\theta$ | incident angle modifier | — |
| $\dot{m}$ | mass flowrate of heat transfer fluid | kg/s |
| $\dot{Q}$ | useful power extracted from collector | W |
| $\dot{Q}_L$ | power loss of collector | W |
| $t$ | time | s |
| $t_a$ | ambient or surrounding air temperature | °C |
| $t_e$ | collector outlet (exit) temperature | °C |
| $t_{in}$ | collector inlet temperature | °C |
| $t_m$ | mean temperature of heat transfer fluid | °C |
| $T$ | absolute temperature | K |
| $T_i^*$ | reduced temperature difference, equation (7) | m² K/W |
| $T_m^*$ | reduced temperature difference, equation (6) | m² K/W |
| $T_s$ | atmospheric or equivalent sky radiation temperature | K |
| $U$ | measured overall heat loss coefficient of collector, with reference to $T_i^*$ | W/(m² K) |

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| Symbol | Meaning | Units |
|---|---|---|
| $\overline{U}$ | measured overall heat loss coefficient of collector, with reference to $T_m^*$ | W/(m² K) |
| $U_L$ | overall heat loss coefficient of a collector with uniform absorber temperature $t_m$ | W/(m² K) |
| $u$ | surrounding air speed | m/s |
| $V_f$ | fluid capacity of the collector | m³ |
| $\Delta p$ | pressure difference between fluid inlet and outlet | Pa |
| $\Delta t$ | time interval | s |
| $\Delta T$ | temperature difference between fluid outlet and inlet ($t_e - t_{in}$) | K |
| $\alpha$ | solar absorptance | — |
| $\beta$ | inclination angle of a plane with respect to horizontal | degrees |
| $\varepsilon$ | hemispherical emittance | — |
| $\theta$ | angle of incidence | degrees |
| $\lambda$ | wavelength | µm |
| $\eta$ | collector thermal efficiency, with reference to $T_i^*$ | — |
| $\overline{\eta}$ | collector thermal efficiency, with reference to $T_m^*$ | — |
| $\eta_0$ | eta zero ($\eta$ at $T_i^* = 0$), reference to $T_i^*$ | — |
| $\overline{\eta}_0$ | eta zero ($\overline{\eta}$ at $T_m^* = 0$), reference to $T_m^*$ | — |
| $\sigma$ | Stefan-Boltzmann constant | W/(m² K⁴) |
| $\rho$ | density of heat transfer fluid | kg/m³ |
| $\tau_c$ | collector time constant | s |
| $\tau$ | transmittance | — |
| $(\tau\alpha)_e$ | product of effective transmittance × absorptance | — |
| $(\tau\alpha)_{ed}$ | product of effective transmittance × absorptance for diffuse solar irradiance | — |
| $(\tau\alpha)_{en}$ | product of effective transmittance × absorptance for direct solar radiation at normal incidence | — |
| $(\tau\alpha)_{e\theta}$ | product of effective transmittance × absorptance for direct solar radiation at angle of incidence $\theta$ | — |

**Subscripts**

| | | |
|---|---|---|
| A | reference to absorber area | — |
| G | reference to gross collector area | — |

1) In the field of solar energy the symbol $G$ is used to denote solar irradiance, rather than the generic symbol $E$ for irradiance.

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# Test Report

| |
|---|
| Collector reference No.: ................ |

| | | | |
|---|---|---|---|
| Test performed by ........................................................................................................................... | | | |
| Address ........................................................................................................................................ | | | |
| Date ................................ | Tel. ................................ | Fax ................................ | Telex ................................ |

## A.2 Solar collector description

**A.2.1 Name of manufacturer** ....................................................................................................................

**and collector model** ...........................................................................................................................

**A.2.2 Collector**

Type: Flat plate ☐ Evacuated tube ☐ Other ☐

Gross area: .................................................................................................................................. $m^2$

Aperture area: ............................................................................................................................. $m^2$

Absorber area: ............................................................................................................................. $m^2$

Number of covers: ..........................................................................................................................

Cover materials: ..............................................................................................................................

Cover thickness: .............................................................................................................................. mm

Number of tubes or channels: ........................................................................................................

Tube diameter or channel dimensions: ........................................................................................... mm

Tube or channel pitch: ..................................................................................................................... mm

**A.2.3 Heat transfer medium**

Type: Water ☐ Oil ☐ Other ☐

Specifications (additives etc.): .......................................................................................................

Alternative acceptable heat transfer fluids: .....................................................................................

**A.2.4 Absorber**

Material: ...........................................................................................................................................

Surface treatment: ...........................................................................................................................

Construction type: ............................................................................................................................

Fluid content: .................................................................................................................................. litres

Weight empty: .................................................................................................................................. kg

Dimensions: ...................................................................................................................................... mm

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Collector reference No.: ................

### A.2.5 Thermal insulation and casing

Thermal insulation thickness: .................................................................................................... mm

Insulation material: ....................................................................................................................

Casing material: ........................................................................................................................

Total mass of collector without fluid: ........................................................................................ kg

Gross dimensions: ................................................................................................................... mm

Aperture dimensions: ............................................................................................................... mm

Sealing material: .......................................................................................................................

### A.2.6 Limitations

Maximum temperature of operation: .......................................................................................... °C

Maximum pressure: ................................................................................................................... Pa

Other limitations: .......................................................................................................................

### A.2.7 Schematic diagram of solar collector (attach separate page if necessary)

### A.2.8 Photograph of the collector (attach separate page if necessary)

### A.2.9 Comments on collector design (attach separate page if necessary)

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| |
|---|
| Collector reference No.: ................ |

**A.2.10 Schematic diagram of collector mounting** (attach separate page if necessary)

Report any special collector mounting

## A.3 Instantaneous efficiency

### A.3.1 Method

Outdoor steady-state conditions ☐ Indoor steady-state conditions ☐

### A.3.2 Schematic diagram of the test loop (attach separate page if necessary)

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Collector reference No.: ................

### A.3.3 Test results, measured and derived data

Latitude: ....................................... Longitude: .......................................

Collector tilt: .................... degrees Collector azimuth: ............................

Local time at solar noon: ...............

**Table A.1 — Test results, measured data**

| **Date** YYMMDD | **LT** h-min | $G$ W/m$^2$ | $G_d/G$ % | $E_L$ W/m$^2$ | $t_a$ °C | $u$ m/s | $t_{in}$ °C | $t_e - t_{in}$ K | $\dot{m}$ kg/s |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

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Collector reference No.: ................

**Table A.2 — Test results, derived data**

| **Date** YYMMDD | **LT** h-min | $t_m$ °C | $c_f$ J/(kg K) | $\dot{Q}$ W | $\frac{t_m - t_a}{G}$ $m^2$ K/W | $\frac{t_{in} - t_a}{G}$ $m^2$ K/W | $\bar{\eta}_G$ | $\eta_G$ | $\bar{\eta}_A$ | $\eta_A$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |

NOTE — Report here any high temperature preconditioning or procedures for measuring simulated solar irradiance.

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Collector reference No.: ................

### A.3.4 Instantaneous efficiency curve based on gross area and mean temperature of heat transfer fluid

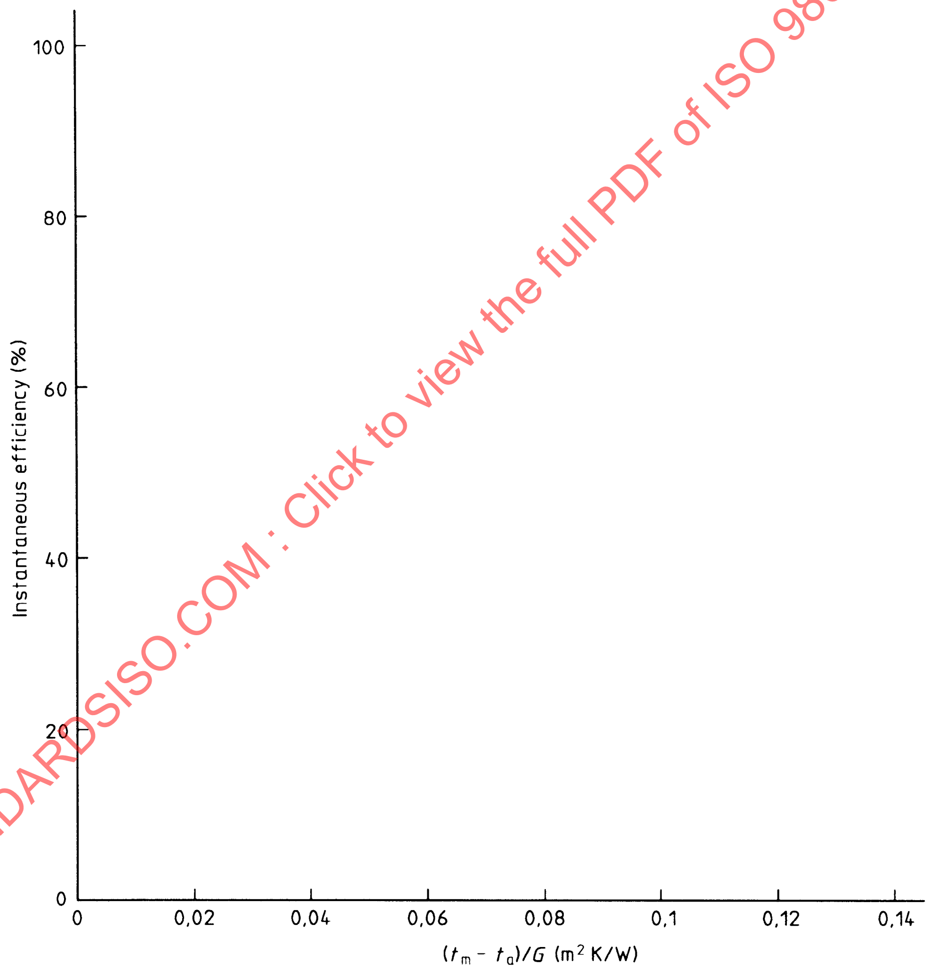
#### A.3.4.1 Linear fit to data

The instantaneous efficiency is defined by: $\bar{\eta}_G = \frac{\dot{Q}}{A_G \, G}$

Gross collector area used for curve: ........................................................................................ $m^2$

Fluid flowrate used for the tests: ........................................................................................ kg/s

Absorber area: ........................................................................................ $m^2$




Linear fit to data: $\bar{\eta}_G = \bar{\eta}_{0G} - \bar{U}_G \frac{t_m - t_a}{G}$

$\bar{\eta}_{0G}$ = ........................................

$\bar{U}_G$ = ........................ $W/(m^2 \, K)$

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Collector reference No.: ................

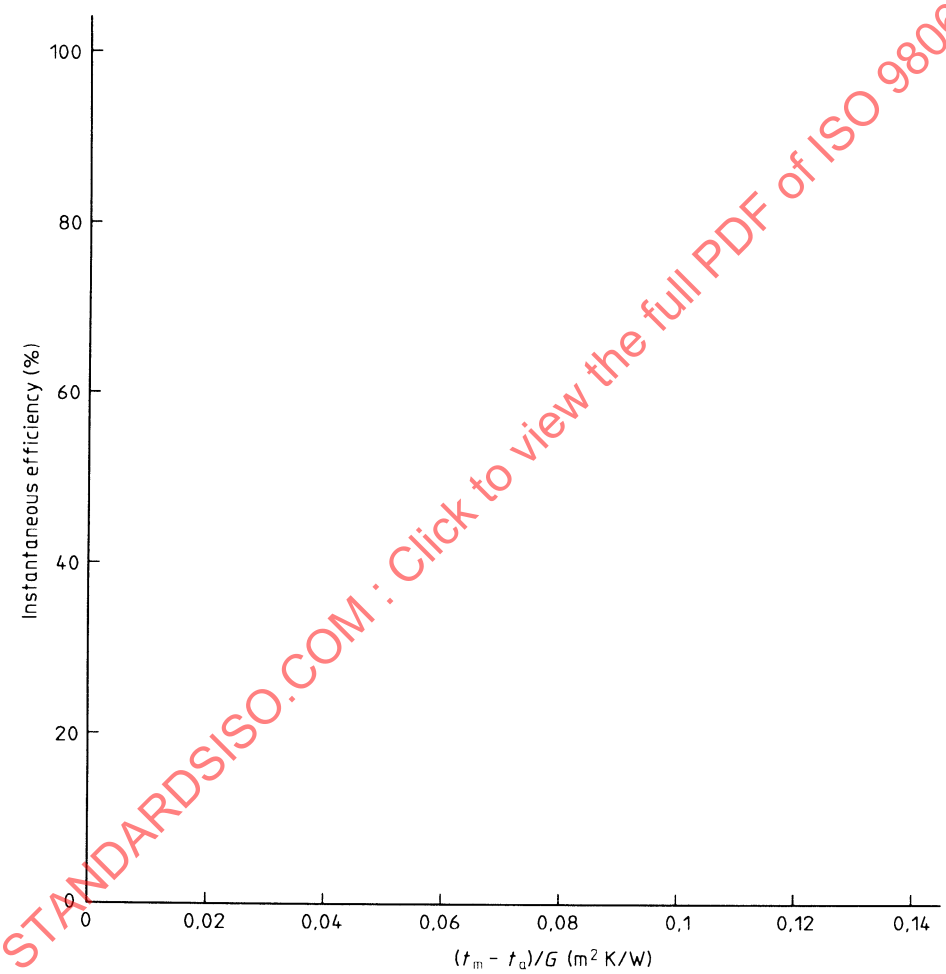
### A.3.4.2 Second-order fit to data

The instantaneous efficiency is defined by: $\bar{\eta}_G = \frac{\dot{Q}}{A_G\, G}$

Gross collector area used for curve: .................... $m^2$

Fluid flowrate used for the tests: .................... kg/s

Absorber area: .................... $m^2$

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Second-order fit to data: $\bar{\eta}_G = \bar{\eta}_{0G} - \bar{a}_{1G} \frac{t_m - t_a}{G} - \bar{a}_{2G}\, G \left( \frac{t_m - t_a}{G} \right)^2$

$\bar{\eta}_{0G}$ = ....................

$\bar{a}_{1G}$ = .................... W/($m^2$ K)

$\bar{a}_{2G}$ = .................... W/($m^2$ $K^2$)

NOTE 14 The value of $G$ to be used for a second-order fit is 800 W/$m^2$.

| Collector reference No.: ................ |
|---|

## A.3.5 Instantaneous efficiency curve based on gross area and collector inlet temperature

### A.3.5.1 Linear fit to data

The instantaneous efficiency is defined by: $\eta_G = \frac{\dot{Q}}{A_G\, G}$

Gross collector area used for curve: .................................................................................................. $m^2$

Fluid flowrate used for the tests: .................................................................................................. kg/s

Absorber area: .................................................................................................. $m^2$

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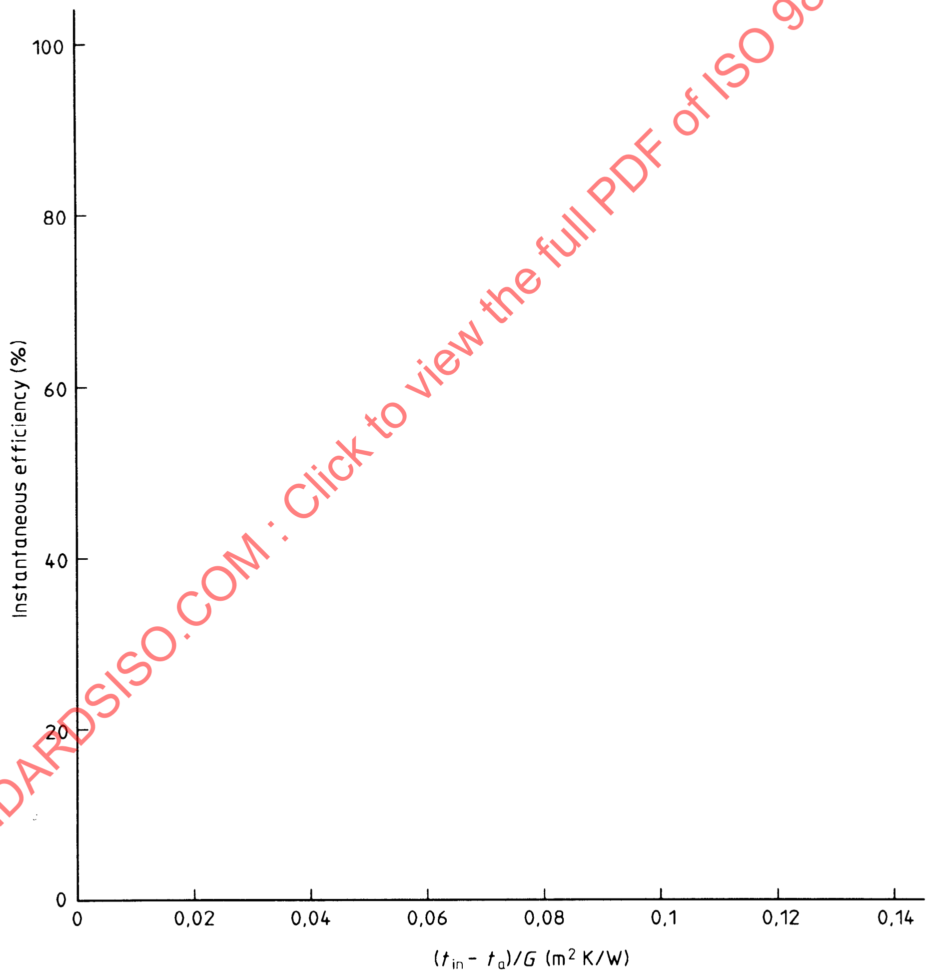



Linear fit to data: $\eta_G = \eta_{0G} - U_G \frac{t_{in} - t_a}{G}$

$\eta_{0G}$ = ......................................

$U_G$ = ........................ W/($m^2$ K)

| |
|---|
| Collector reference No.: ................ |

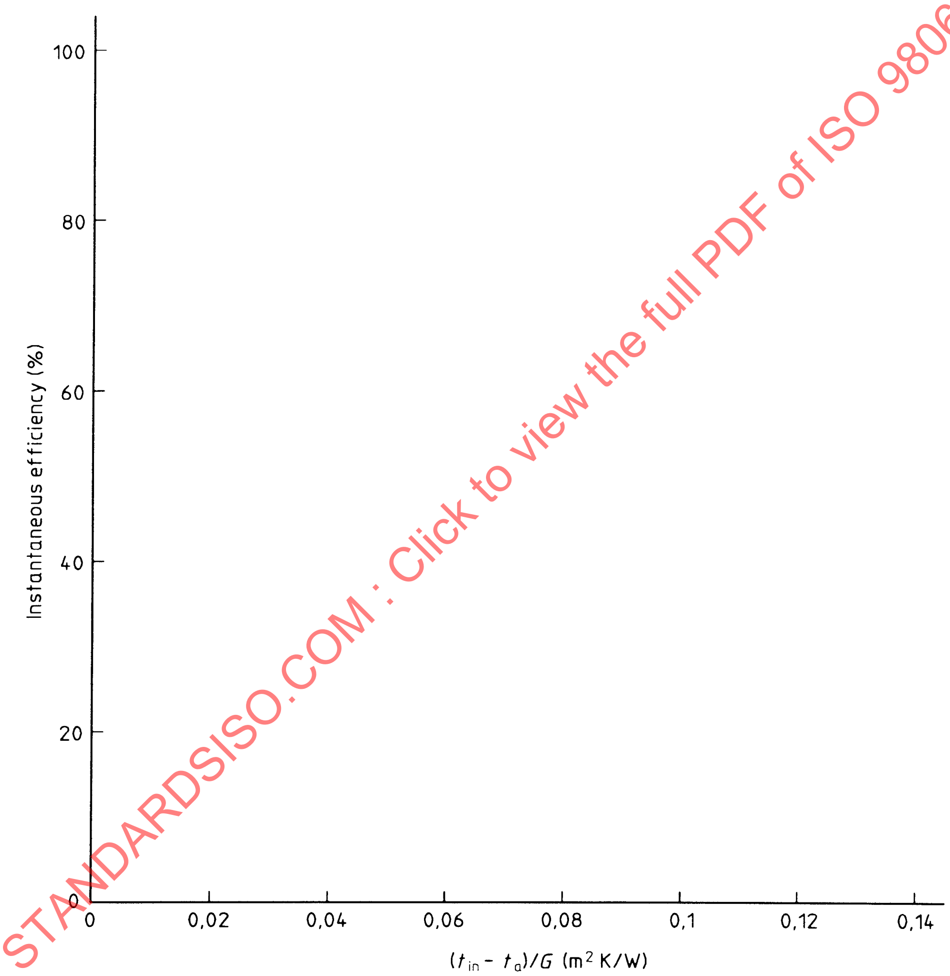
### A.3.5.2 Second-order fit to data

The instantaneous efficiency is defined by: $\eta_G = \frac{\dot{Q}}{A_G\ G}$

Gross collector area used for curve: .................................................. $m^2$

Fluid flowrate used for the tests: .................................................. kg/s

Absorber area: .................................................. $m^2$

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Second-order fit to data: $\eta_G = \eta_{0G} - a_{1G} \frac{t_{in} - t_a}{G} - a_{2G}\ G \left( \frac{t_{in} - t_a}{G} \right)^2$

$\eta_{0G}$ = ........................................

$a_{1G}$ = ......................... W/($m^2$ K)

$a_{2G}$ = ....................... W/($m^2$ $K^2$)

NOTE 15 The value of $G$ to be used for a second-order fit is 800 W/$m^2$.

| |
|---|
| Collector reference No.: ................ |

## A.3.6 Instantaneous efficiency curve based on absorber area and mean temperature of heat transfer fluid

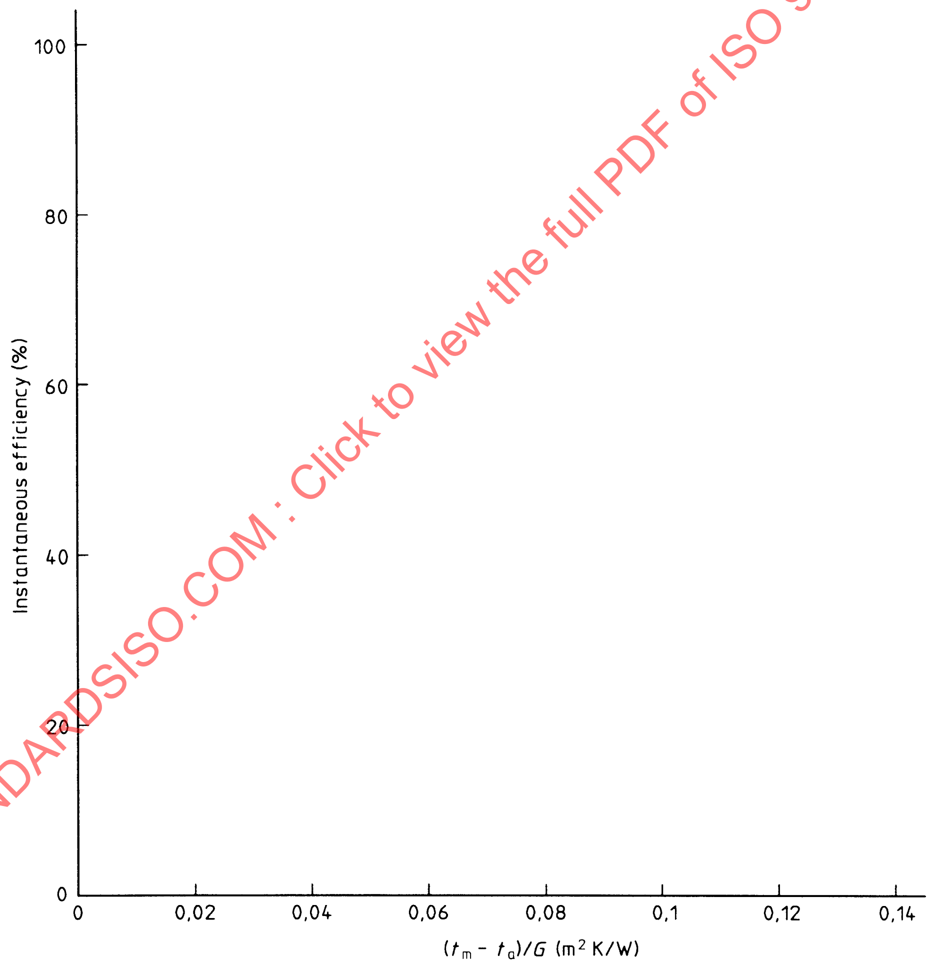
### A.3.6.1 Linear fit to data

The instantaneous efficiency is defined by: $\overline{\eta}_A = \dfrac{\dot{Q}}{A_A\ G}$

Absorber area used for curve: .................................................................................... $m^2$

Fluid flowrate used for the tests: .................................................................................... kg/s

Gross collector area: .................................................................................... $m^2$




Linear fit to data: $\overline{\eta}_A = \overline{\eta}_{0A} - \overline{U}_A \dfrac{t_m - t_a}{G}$

$\overline{\eta}_{0A}$ = .......................................

$\overline{U}_A$ = ......................... W/($m^2$ K)

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### A.3.6.2 Second-order fit to data

The instantaneous efficiency is defined by: $\bar{\eta}_A = \frac{\dot{Q}}{A_A\, G}$

Absorber area used for curve: .................................................................................................... $m^2$

Fluid flowrate used for the tests: .................................................................................................... kg/s

Gross collector area: .................................................................................................... $m^2$

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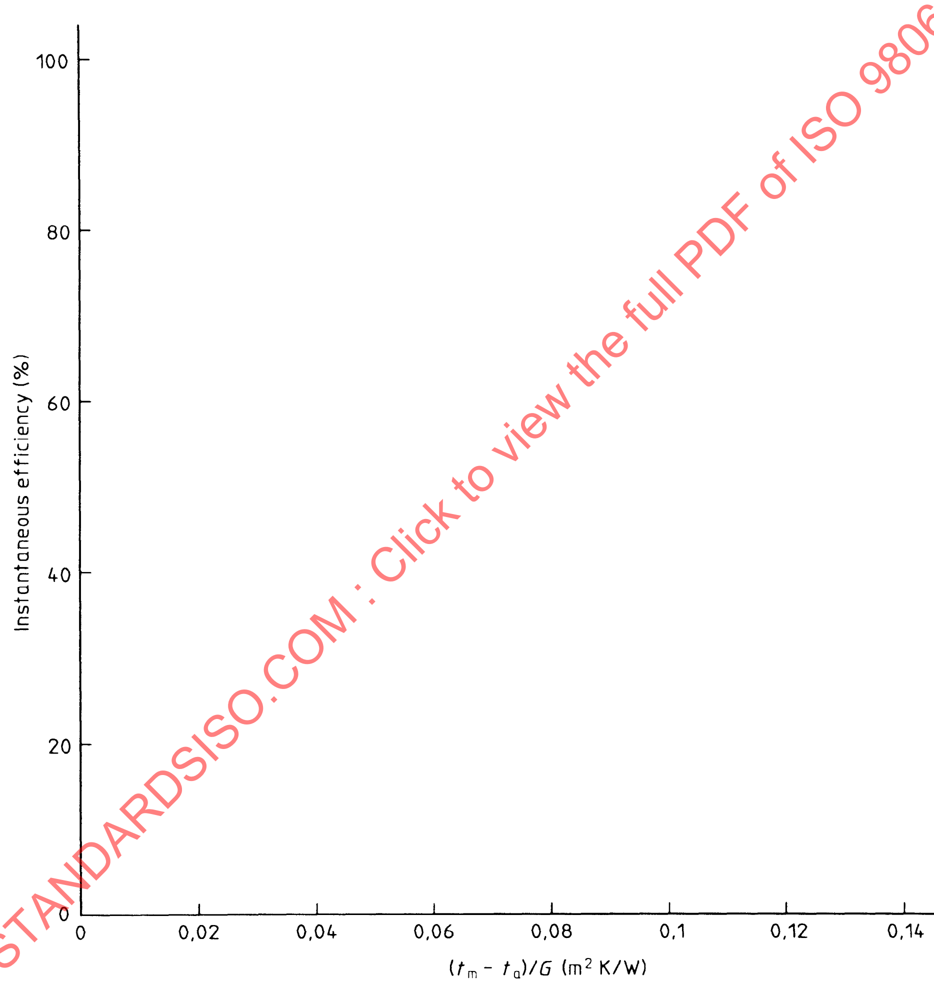



Second-order fit to data: $\bar{\eta}_A = \bar{\eta}_{0A} - \bar{a}_{1A} \frac{t_m - t_a}{G} - \bar{a}_{2A}\, G \left( \frac{t_m - t_a}{G} \right)^2$

$\bar{\eta}_{0A}$ = .......................................

$\bar{a}_{1A}$ = ......................... W/($m^2$ K)

$\bar{a}_{2A}$ = ....................... W/($m^2$ $K^2$)

NOTE 16 The value of $G$ to be used for a second-order fit is 800 W/$m^2$.

Collector reference No.: ................

### A.3.7 Instantaneous efficiency curve based on absorber area and collector inlet temperature

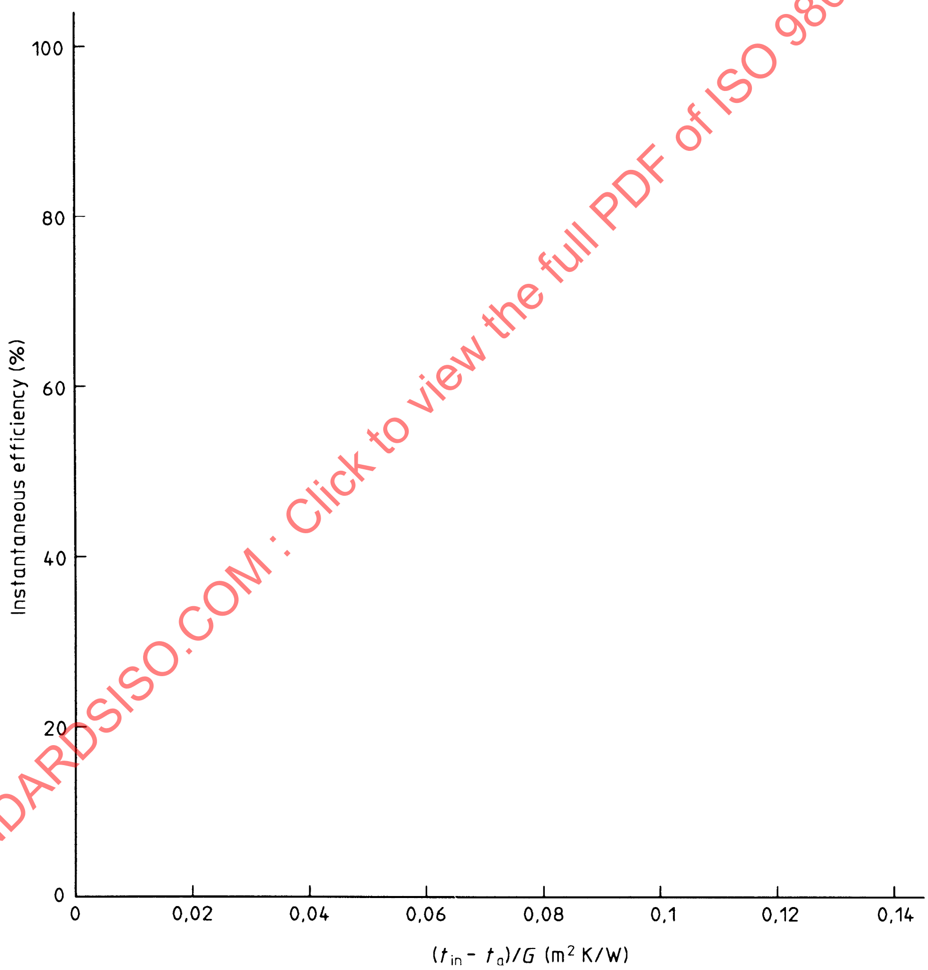
#### A.3.7.1 Linear fit to data

The instantaneous efficiency is defined by: $\eta_A = \frac{\dot{Q}}{A_A G}$

Absorber area used for curve: .................................................................................................... $m^2$

Fluid flowrate used for the tests: .................................................................................................... kg/s

Gross collector area: .................................................................................................... $m^2$




Linear fit to data: $\eta_A = \eta_{0A} - U_A \frac{t_{in} - t_a}{G}$

$\eta_{0A}$ = ......................................

$U_A$ = ........................ W/(m² K)

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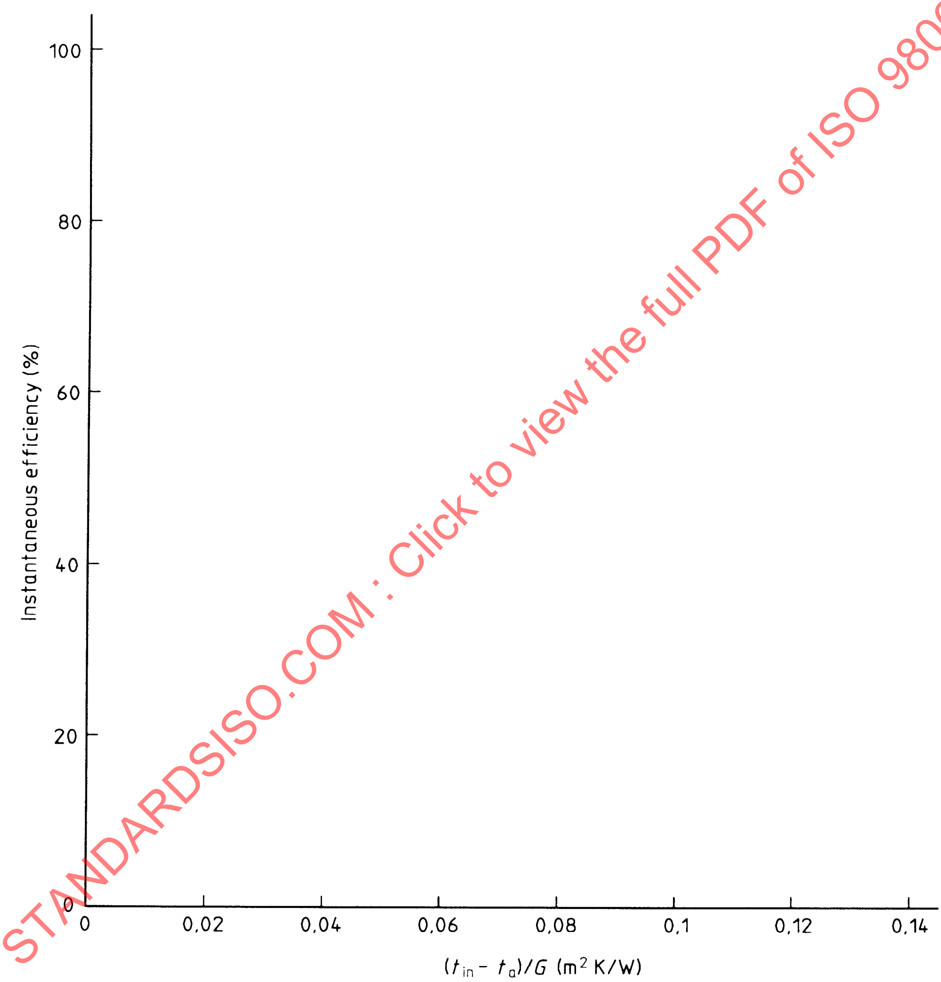
### A.3.7.2 Second-order fit to data

The instantaneous efficiency is defined by: $\eta_A = \frac{\dot{Q}}{A_A\,G}$

Absorber area used for curve: .................................................. $m^2$

Fluid flowrate used for the tests: .................................................. kg/s

Gross collector area: .................................................. $m^2$

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Second-order fit to data: $\eta_A = \eta_{0A} - a_{1A}\,\frac{t_{in} - t_a}{G} - a_{2A}\,G\left(\frac{t_{in} - t_a}{G}\right)^2$

$\eta_{0A}$ = ........................................

$a_{1A}$ = ......................... W/($m^2$ K)

$a_{2A}$ = ....................... W/($m^2$ $K^2$)

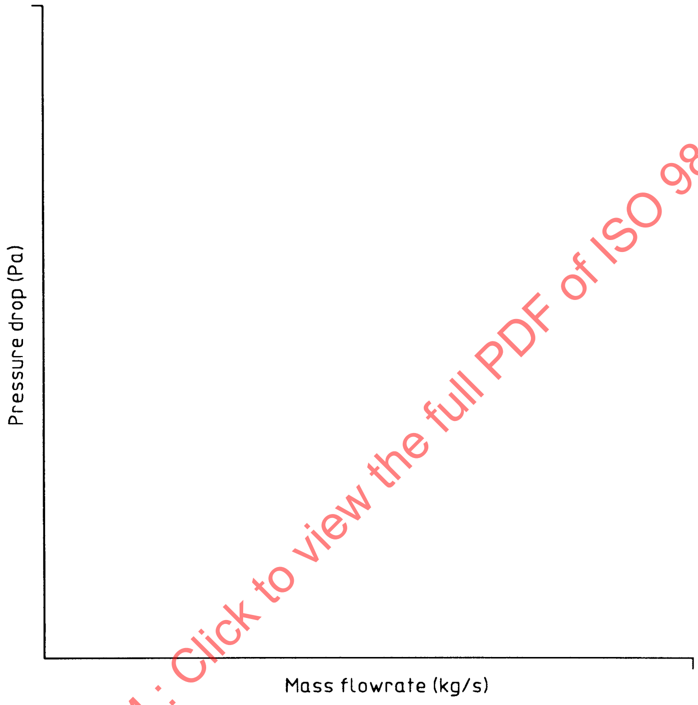
NOTE 17 The value of $G$ to be used for a second-order fit is 800 W/$m^2$.

Collector reference No.: ................

## A.4 Pressure drop

Fluid: ..............................................................................................................................................

Temperature: ........................................................................................................................ °C

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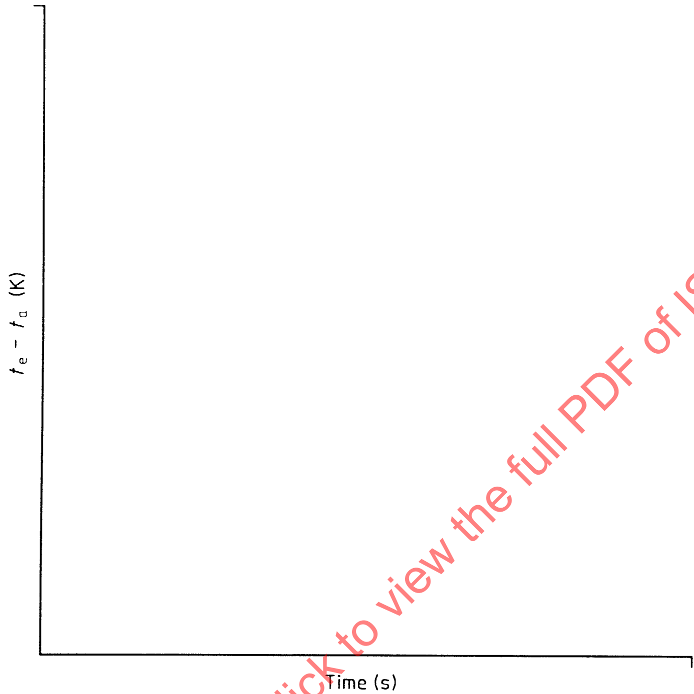
| Collector reference No.: ................ |
|---|

**A.5 Time constant**

$\tau_c$ = ...................................... s

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Collector reference No.: ................

## A.6 Effective thermal capacity

$C$ = ........................................ J/K

Determination:

Calculation: ....................

Indoors: .........................

Outdoors: ......................

NOTE 18 The effective thermal capacity is calculated from the measurement records of $t_{in}$, $\Delta T$, $t_a$ and by the following relation for indoor testing

$$C = \frac{-\dot{m}\, c_f \int_{t_1}^{t_2} \Delta T \, dt - A_G\, \bar{U}_G \left[ \int_{t_1}^{t_2} (t_{in} - t_a)\, dt + \frac{1}{2} \int_{t_1}^{t_2} \Delta T \, dt \right]}{t_{m2} - t_{m1}}$$

or from the measurement records of $t_{in}$, $\Delta T$, $t_a$, $G$ and by the following relation for outdoor testing:

$$C = \frac{A_G\, \bar{\eta}_{0G} \int_{t_1}^{t_2} G \, dt - \dot{m}\, c_f \int_{t_1}^{t_2} \Delta T \, dt - A_G\, \bar{U}_G \left[ \int_{t_1}^{t_2} (t_{in} - t_a)\, dt + \frac{1}{2} \int_{t_1}^{t_2} \Delta T \, dt \right]}{t_{m2} - t_{m1}}$$

## A.7 Incident angle modifier

| **Angle** | 0° | 30° | 45° | 60° | 70° |
|---|---|---|---|---|---|
| $K_\theta$ | | | | | |


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# Annex B
(informative)

# Collector characteristics

## B.1 General

The thermal performance of flat plate collectors, operating under steady-state conditions, can be expressed as a function of either the mean temperature of the heat transfer fluid $t_m$ or the collector inlet temperature $t_{in}$. Furthermore, the gross collector area or the absorber area can be used as a reference area for the thermal efficiency.

### B.1.1 Basic equations using collector mean temperature

The thermal performance of flat plate solar collectors operating under steady-state conditions, as a function of the collector mean temperature $t_m$ and the collector gross area $A_G$, can be described by the following relationship:

$$\frac{\dot{Q}}{A_G} = F' (\tau\alpha)_e G - F' U_L (t_m - t_a) \qquad \ldots (B.1)$$

or expressed in terms of measured parameters

$$\frac{\dot{Q}}{A_G} = \dot{m} c_f \frac{t_e - t_{in}}{A_G} \qquad \ldots (B.2)$$

The thermal efficiency is then given by:

$$\bar{\eta}_G = \frac{\dot{Q}}{A_G G} = F' (\tau\alpha)_e - F' U_L \frac{(t_m - t_a)}{G} = \dot{m} c_f \frac{t_e - t_{in}}{A_G G} \qquad \ldots (B.3)$$

Equation (B.3) indicates that if the efficiency for a solar collector is plotted against $(t_m - t_a)/G$, then a straight line will result provided $U_L$ is a constant. The slope of the line will equal $F' U_L$ and the $y$ intercept will equal $F' (\tau\alpha)_e$.

In reality, $U_L$ is not a constant but is a function of the temperature of the absorber plate and the ambient weather conditions. Although equation (B.3) may suffice for many solar collectors, some collectors may require the use of a higher-order equation to account for these effects. It has been proposed that the variation in $U_L$ may be better represented by a linear relationship involving $(t_m - t_a)$. Thus, letting

$$F' U_L = b + c (t_m - t_a) \qquad \ldots (B.4)$$

where $b$ and $c$ are coefficients, equation (B.1) becomes

$$\frac{\dot{Q}}{A_G} = F' (\tau\alpha)_e G - b(t_m - t_a) - c(t_m - t_a)^2 \qquad \ldots (B.5)$$

or, in terms of efficiency,

$$\bar{\eta}_G = F' (\tau\alpha)_e - b \frac{(t_m - t_a)}{G} - c \frac{(t_m - t_a)^2}{G} \qquad \ldots (B.6)$$

In the case of equation (B.6), if values of efficiency are plotted against $(t_m - t_a)/G$ a second-order curve will result.

Equations (B.3) and (B.6) are written again in a form compatible with the symbols given in clause A.1.

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With reference to $t_m$ and $A_G$, the equations for the instantaneous thermal efficiency are:

$$\bar{\eta}_G = F' (\tau\alpha)_e - F' U_L \frac{t_m - t_a}{G} \qquad \ldots (B.7)$$

and

$$\bar{\eta}_G = F' (\tau\alpha)_e - \bar{a}_{1G} \frac{t_m - t_a}{G} - \bar{a}_{2G} G \left( \frac{t_m - t_a}{G} \right)^2 \qquad \ldots (B.8)$$

With reference to mean temperature of the heat transfer fluid $t_m$ and the absorber area $A_A$, the equations for the instantaneous thermal efficiency can easily be derived from equations (B.7) and (B.8), noting that:

$$\bar{\eta}_A = \bar{\eta}_G \frac{A_G}{A_A} \qquad \ldots (B.9)$$

### B.1.2 Basic equations using collector inlet temperature

The thermal performance of flat plate collectors under steady-state conditions, as a function of the collector inlet temperature $t_{in}$ and the collector gross area $A_G$, can be described by the following relationship:

$$\frac{\dot{Q}}{A_G} = F_R(\tau\alpha)_e G - F_R U_L (t_{in} - t_a) \qquad \ldots (B.10)$$

or expressed in terms of the measured parameters as given in equation (B.2):

$$\frac{\dot{Q}}{A_G} = \dot{m} c_f \frac{t_e - t_{in}}{A_G}$$

The thermal efficiency is then given by

$$\eta_G = \frac{\dot{Q}}{A_G G} = F_R(\tau\alpha)_e - F_R U_L \frac{t_{in} - t_a}{G} = \dot{m} c_f \frac{t_e - t_{in}}{A_G G} \qquad \ldots (B.11)$$

Equation (B.11) indicates that if the efficiency for a solar collector is plotted against $(t_{in} - t_a)/G$, then a straight line will result provided $U_L$ is a constant. The slope of the line will equal $F_R U_L$ and the $y$ intercept will equal $F_R (\tau\alpha)_e$.

It has been mentioned in B.1.1 that $U_L$ is not constant but is a function of the temperature of the absorber plate and the ambient temperature. A procedure, similar to that in B.1.1, can be followed to express instantaneous efficiency, $\eta_G$, with a second-order equation.

With reference to $t_{in}$ and $A_G$, the equations for the instantaneous thermal efficiency of a collector are

$$\eta_G = F_R (\tau\alpha)_e - F_R U_L \frac{t_{in} - t_a}{G} \qquad \ldots (B.12)$$

and

$$\eta_G = F_R(\tau\alpha)_e - a_{1G} \frac{t_{in} - t_a}{G} - a_{2G} G \left( \frac{t_{in} - t_a}{G} \right)^2 \qquad \ldots (B.13)$$

With reference to collector inlet temperature $t_{in}$ and the absorber area $A_A$, the equations for the instantaneous thermal efficiency can be easily derived from equations (B.12) and (B.13), noting that

$$\eta_A = \eta_G \frac{A_G}{A_A} \qquad \ldots (B.14)$$

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### B.1.3 Thermal performance test data conversion

The collector instantaneous thermal efficiency, in terms of the collector mean temperature $t_m$ and the collector gross area $A_G$ and in linear form, is described by the equation (B.7), i.e.:

$$\bar{\eta}_G = F' (\tau\alpha)_e - F'U_L \frac{t_m - t_a}{G}$$

In terms of the collector inlet temperature and the collector gross area $A_G$, (B.12) is the corresponding linear equation for the instantaneous efficiency, i.e.:

$$\eta_G = F_R (\tau\alpha)_e - F_R U_L \frac{t_{in} - t_a}{G}$$

If the flowrate $\dot{m}$ of the thermal transfer fluid is known, then, by assuming a linear temperature rise across the collector, the $y$ intercept $F_R(\tau\alpha)_e$ and the slope $F_RU_L$ of equation (B.12) are related to the corresponding values of $F'(\tau\alpha)_e$ and $F'U_L$ of equation (B.7) by the following:

$$F_R(\tau\alpha)_e = F'(\tau\alpha)_e \left[ \frac{\zeta}{\zeta + \frac{F'U_L}{2}} \right] \quad \text{. . . (B.15)}$$

$$F_R U_L = F'U_L \left[ \frac{\zeta}{\zeta + \frac{F'U_L}{2}} \right] \quad \text{. . . (B.16)}$$

where

$$\zeta = \frac{\dot{m}\, c_f}{A_G}$$

Equations (B.15) and (B.16) can be used to convert from one set of performance characteristics to the other.

## B.2 Collector time constant

The governing equation for the transient behaviour of a solar collector, using the flat plate collector as an example, is:

$$C \frac{dt_m}{A_G\, dt} = F'\, G\, (\tau\alpha)_e - F'U_L(t_m - t_a) - \frac{\dot{m}\, c_f}{A_G} (t_e - t_{in}) \quad \text{. . . (B.17)}$$

If (a) the solar radiation $G$, or inlet fluid temperature $t_{in}$ are suddenly changed and then held constant, and if (b) $(\tau\alpha)_e$, $U_L$, $t_a$, $\dot{m}$, and $c_f$ can be considered constant for the transient period, and if (c) the rate of change in heat transfer fluid exit temperature with time is related to the rate of change in the heat transfer fluid average temperature with time by:

$$\frac{dt_m}{dt} = K \frac{dt_e}{dt} \quad \text{. . . (B.18)}$$

where

$$K = \left( \frac{\dot{m}\, c_f}{F'\, U_L\, A_G} \right) \left( \frac{F'}{F_R} - 1 \right)$$

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