INTERNATIONAL STANDARD

ISO 9459-5

First edition
2007-05-15

Solar heating — Domestic water heating systems —

Part 5: System performance characterization by means of whole-system tests and computer simulation

Chauffage solaire — Systèmes de chauffage de l'eau sanitaire —

Partie 5: Caractérisation de la performance des systèmes au moyen d'essais effectués sur l'ensemble du système et par simulation sur ordinateur

Reference number
ISO 9459-5:2007(E)

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. 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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 9459-5 was prepared by Technical Committee ISO/TC 180, *Solar energy*, Subcommittee SC 4, *Systems — Thermal performance, reliability and durability*.

ISO 9459 consists of the following parts, under the general title *Solar heating — Domestic water heating systems*:

— *Part 1: Performance rating procedure using indoor test methods*

— *Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems*

— *Part 3: Performance test for solar plus supplementary systems* (withdrawn)

— *Part 4: System performance characterization by means of component tests and computer simulation*

— *Part 5: System performance characterization by means of whole-system tests and computer simulation*

Introduction

International Standard ISO 9459 has been developed to help facilitate the international comparison of solar domestic water heating systems. Because a generalized performance model which is applicable to all systems has not yet been developed, it has not been possible to obtain an international consensus for one test method and one standard set of test conditions. It has therefore been decided to promulgate the currently available simple test methods, while work continues to finalize the more broadly applicable procedures. The advantage of this approach is that each part can proceed on its own.

ISO 9459 is divided into five parts within three broad categories, as described below.

Rating test

ISO 9459-1:1993, *Solar heating — Domestic water heating systems — Part 1: Performance rating procedure using indoor test methods,* involves testing for periods of 1 day for a standardized set of reference conditions. The results, therefore, allow systems to be compared under identical solar, ambient and load conditions.

Black-box correlation procedures

ISO 9459-2:1995, *Solar heating — Domestic water heating systems — Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems*, is applicable to solar-only systems and solar-preheat systems. The performance test for solar-only systems is a 'black-box' procedure which produces a family of 'input-output' characteristics for a system. The test results may be used directly with daily mean values of local solar irradiation, ambient air temperature and cold-water temperature data to predict annual system performance.

ISO 9459-3:1997, *Solar heating — Domestic water heating systems — Part 3: Performance test for solar plus supplementary systems* (now withdrawn), applied to solar plus supplementary systems. The performance test was a 'black-box' procedure which produced coefficients in a correlation equation that could be used with daily mean values of local solar irradiation, ambient air temperature and cold-water temperature data to predict annual system performance. The test was limited to predicting annual performance for one load pattern.

Testing and computer simulation

ISO/AWI 9459-4, *Solar heating — Domestic water heating systems — Part 4: System performance characterization by means of component tests and computer simulation*, a procedure for characterizing annual system performance, uses measured component characteristics in the computer simulation program 'TRNSYS'. Procedures for characterizing the performance of system components other than collectors are also presented in this part of ISO 9459. Procedures for characterizing the performance of collectors are given in other International Standards.

This part of ISO 9459 (i.e. ISO 9459-5) presents a procedure for dynamic testing of complete systems to determine system parameters for use in the "Dynamic System Testing Program" (reference [2]). This software has been validated on a range of systems; however, it is a proprietary product and cannot be modified by the user. Implementation of the software requires training from a test facility experienced with the application of the product. This model may be used with hourly values of local solar irradiation, ambient air temperature and cold-water temperature data to predict annual system performance.

The procedures defined in ISO 9459-2, ISO 9459-3, ISO 9459-4 and ISO 9459-5 for predicting yearly performance allow the output of a system to be determined for a range of climatic conditions.

The results of tests performed in accordance with ISO 9459-1 provide a rating for a standard day.

The results of tests performed in accordance with ISO 9459-2 permit performance predictions for a range of system loads and operating conditions, but only for an evening draw-off.

The results of tests performed in accordance with ISO 9459-3 permitted annual system predictions for one daily load pattern.

The results of tests performed in accordance with ISO 9459-4 or ISO 9459-5 are directly comparable. These procedures permit performance predictions for a range of system loads and operating conditions.

System reliability and safety will be dealt with in ISO 11924, *Solar heating — Domestic water heating systems — Test methods for the assessment of protection from extreme temperatures and pressures*.

Introduction to ISO 9459-5

The expanding market for Solar Domestic Hot-water (SDHW) systems demands a standardized test method for SDHW systems, which makes possible accurate long-term performance prediction for arbitrary conditions from a test as short, simple and cheap as possible.

Two facts make this goal difficult to reach.

a) The SDHW system gain depends on many different conditions (e.g., irradiance, ambient temperature, draw-off profile and cold-water temperature). Therefore, a sufficient number of parameters are needed to predict the yearly system gain sufficiently accurately for arbitrary conditions.

b) The system state, that is, the temperature profile inside the store, needs a long time to 'forget' initial conditions; a typical time constant may be one day or more. Since several parameters need to be determined, several system states must occur during the test. If a test method did not take into account the system state dependence on the past, and thus the dynamic behaviour of the system, the minimum testing times would be quite long (up to several months).

The objective of the method described in this part of ISO 9459 is to minimize experimental effort by keeping the test duration short and avoiding extensive measurements. To compensate for the relatively small amount of experimental data, mathematical tools are used to extract as much information as possible from the test data, while being robust enough to avoid being misled by unimportant transient effects.

There are no requirements for steady-state conditions in the tests, and, due to the 'black-box' approach, no measurements inside the store or inside the collector loop are required.

Experience has shown that the variability of system states encompassed by the test sequence is the most important precondition for the correct determination of all system parameters with minimum errors and cross correlation between parameters. Only if the system is driven into many different states, is the influence of each parameter of the model shown on the performance of the system. Therefore, the overall design criterion of a draw-off test sequence is that the system shall be driven into as many different states as possible in a minimum time. Here, system state means a combination of the store temperature distribution and weather conditions. The system states should include all states that may occur in actual operation. For testing purposes, it is much more important to have a large variability of system states than to perform draw-offs according to 'normal user behaviour'. Accurate parameter identification will be achieved only if the range of system states in actual operation is covered by the range of system states set up during the tests. The method is applicable to in-situ monitoring, but difficulties arise during in-situ testing, as the operator cannot control the operating conditions. Monitoring of 'normal user behaviour' needs to be carried out over a long time to ensure that all relevant system states are covered, i.e. testing times can be much longer to achieve the same performance prediction accuracy.

This part of ISO 9459 may be applicable to a wide range of systems, including systems with relatively large collectors which have to be cooled by large, frequent draw-offs to prevent overheating, and systems with relatively large storage tanks which need to be operated with low loads for days, in order to reach the high store and collector temperatures needed for accurate parameter identification. No single draw-off profile can meet these demands for all systems, since the ratio of storage volume and collector aperture area (V_S/A_C) may vary up to a factor of 20 for the systems considered in this this part of ISO 9459. Therefore, the draw-off volumes have been made dependent on V_S and V_S/A_C.

Experience has shown that the system state variability is especially important for the determination of the effective collector area A_C^*, the effective collector loss coefficient u_C^* and the store-loss coefficient U_S.

To discern between optical and thermal collector properties, the store (and thus the collector inlet temperature) must be kept cold for some intervals with substantial irradiance (Test A) and then be allowed to become hot while irradiance is sufficient to keep the collector loop operational (Test B).

To discern between store losses (which happen all the time) and collector losses (which happen only when there is sufficient irradiance), the store must be operated at high temperatures during some periods with low irradiance.

Solar heating — Domestic water heating systems —

Part 5: System performance characterization by means of whole-system tests and computer simulation

1 Scope

This part of ISO 9459 specifies a method for outdoor laboratory testing of solar domestic hot-water (SDHW) systems. The method may also be applied for in-situ tests, and also for indoor tests by specifying appropriate draw-off profiles and irradiance profiles for indoor measurements. The system performance is characterized by means of whole-system tests using a 'black-box' approach, i.e. no measurements on the system components or inside the system are necessary. Detailed instructions are given on the measurement procedure, on processing and analysis of the measurement data, and on presentation of the test report.

The theoretical model described in reference [1] is used to characterize SDHW system performance under transient operation. The identification of the parameters in the theoretical model is carried out by a parameter-identification software program (see Annex A). The program finds the set of parameters that gives the best fit between the theoretical model and the measured data.

A wide range of operating conditions shall be covered to ensure accurate determination of the system parameters. Measured data shall be pre-processed before being used for identification of system parameters. The identified parameters are used for the prediction of the long-term system performance for the climatic and load conditions of the desired location, using the same model as for parameter identification. The system prediction part of the theoretical model requires hourly values of meteorological data (e.g. test reference years) and specific load data, as described in Annex C.

This part of ISO 9459 can be applied to the following SDHW systems including:

a) systems with forced circulation of fluid in the collector loop;

b) thermosiphon systems;

c) integral collector storage (ICS) systems;.

provided that for b) and c) the validation requirements described in Clause B.2 of Annex B are satisfied.

Systems are limited to the following dimensions[1)].

— The collector aperture area of the SDHW system is between 1 and 10 m^2.

— The storage capacity of the SDHW system is between 50 and 1 000 litres.

— The specific storage-tank volume is between 10 and 200 litres per square metre of collector aperture area.

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1) In general there are no restrictions on the size of a system being tested however validation tests of the method for systems with more than 10 m^2 collector area are not available. The system size may affect details of the procedure, hence application to systems outside of the specified range requires validation tests (see Annex B).

Limits to the application of this International Standard.

1) This part of ISO 9459 is not intended to establish any safety or health requirements.

2) This part of ISO 9459 is not intended to be used for testing the individual components of the system. However, it is permitted to obtain test data of components in combination with a test according to the procedure described here.

3) The test procedure cannot be applied to SDHW systems containing more than one storage tank. This does not exclude preheat systems with a second tank in series. However, only the first tank is considered as part of the system being tested.

4) Systems with collectors having non-flat plate-type incident-angle characteristics can be tested if the irradiance in the data file(s) is multiplied by the measured incident-angle modifier prior to parameter identification. The same irradiance correction should, in this case, also be used during any performance predictions based on the identified parameters.

5) The test procedure cannot be applied to SDHW systems with overheating protection devices that significantly influence the system behaviour under normal operation[2)].

6) The test procedure cannot be applied to integrated auxiliary solar systems, with a high proportion of the store heated concurrently by the auxiliary heater. The results of the tests are only valid when the resulting parameter $f_{aux} < 0,75$.

7) The test procedure cannot be applied to SDHW systems with an external load-side heat exchanger in combination with a temperature-dependent pump.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

ISO 9459-2, *Solar heating — Domestic water heating systems — Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems*

ISO 9488:1999, *Solar energy — Vocabulary*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 9488 and the following apply.

3.1
capacitance rate
product of volume draw-off rate, density and mass specific heat of the heat transfer fluid, i.e. the potential of a fluid flow to carry thermal power per unit temperature increase between inlet and outlet

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2) These systems can be tested if the predicted performance is corrected for the influence of the overheating device. A validation test would be required to extend the procedure to such systems.

3.2
cold-water mixer
device providing potable water of constant temperature to the user by mixing draw-off water and mains water

3.3
collector azimuth angle
azimuth angle of the collector defined similarly to the solar azimuth angle

See 1.4 in ISO 9488:1999.

3.4
components
parts of the solar hot-water system

EXAMPLES Collectors, store, pumps, heat exchanger, controls.

3.5
differential temperature controller
device that is able to detect a small temperature difference, and to control pumps and other electrical devices according to this temperature difference

3.6
draw-off temperature
temperature of hot water withdrawn from the system

3.7
dynamic system testing
procedure which uses the same analytical basis to account for time-varying processes in parameter identification and performance prediction

3.8
external auxiliary heating
auxiliary heater located outside of the storage tank and having no impact on the operation of the solar heating system

3.9
integrated auxiliary heating
auxiliary heater that can influence the operation of the solar heating system

3.10
load-side heat exchanger
device to transfer the heat from a solar store containing non-potable water to potable mains water drawn off

3.11
test duration
total elapsed time for a particular test sequence

3.12
transient conditions
meteorological and system operation conditions varying in time

3.13
parameters
coefficients of the mathematical model characterizing the system as identified by the test procedure

3.14
heat capacity of the store
amount of sensible heat that can be stored per kelvin of temperature increase

3.15
test sequence
continuous measurement including compulsory conditioning at the beginning

3.16
threshold temperature
temperature below which the water is considered to be unsuitable for use

4 Symbols, units and nomenclature

Symbols marked by (**P**) denote model parameters to be determined by the parameter identification.

Symbol	Units	Meaning
A_C	[m^2]	Collector aperture area
A_C^*	[m^2]	Effective collector loop area, $A_C^* = F_R^*(\alpha\tau)A_C$ (**P**)
c_w (T_{cw}, T_S)	[kJ/kgK]	Specific heat of water, averaged over the temperature interval [T_{cw}; T_S] (see Annex D)
C_F	[MJK^{-1}]	Filter constant with regard to the load draw-off
C_S	[MJK^{-1}]	Heat capacity of the store (**P**)
D_L	[-]	Draw-off mixing parameter (**P**)
$\dot{C}_S$	[WK^{-1}]	Load-side heat capacitance rate through the store
f_{aux}	[-]	Fraction of the store heated by the auxiliary heater (**P**)
F_R^*	[-]	Heat removal factor of the collector loop
G_t	[Wm^{-2}]	Solar irradiance in the collector plane
h	[rad]	Solar elevation
I_0	[Wm^{-2}]	Solar constant
P_{aux}	[W]	Auxiliary power entering store
P_{cp}	[W]	Collector loop pumping power
P_L	[W]	Load power, $P_L = \dot{C}_S\left(T_S - T_{cw}\right)$
P_{net}	[W]	Net system power, $P_{net} = P_L - P_{aux}$
Q_L	[MJ]	Load energy
Q_{aux}	[MJ]	Energy from auxiliary heating
Q_{net}	[W]	Net system gain $Q_{net} = \int P_{net}\,\mathrm{d}t = \int\left(\dot{C}_S\left(T_S - T_{cw}\right) - P_{aux}\right)\mathrm{d}t$
R_L	[K/W]	Thermal resistance of load-side heat exchanger (**P**)
S_C	[-]	Collector loop stratification parameter (**P**)
t	[h:min:s]	Time
t_0	[h:min:s]	Actual start time of the first draw-off of the day
T_{ca}	[°C]	Ambient air temperature in vicinity of collectors

T_{cw}	[°C]	Cold (mains) water temperature
T_D	[°C]	Temperature demanded by the user
T_S	[°C]	Outlet temperature of the store
T_{minS}	[°C]	Minimum outlet temperature of the store
T_{sa}	[°C]	Ambient air temperature in vicinity of the store
u_C	[$Wm^{-2}K^{-1}$]	Heat-loss coefficient of the collector loop
u_C^*	[$Wm^{-2}K^{-1}$]	$u_C^* = u_C / (\alpha\tau)$ (**P**)
U_S	[WK^{-1}]	Heat-loss rate of the store per unit temperature difference (**P**)
u_v	[$Jm^{-3}K^{-1}$]	Dependence of u_C on surrounding air velocity (**P**)
v	[ms^{-1}]	Surrounding air velocity
V_S	[l]	Storage-tank volume
$\dot{V}_S$	[l/min]	Volumetric flow through the store
v_{ignore}	[ms^{-1}]	Wind velocity over the collector as used in the in situ software (reference [2]) (not used but is recorded)
v_{force}	[ms^{-1}]	Wind velocity over the collector as used in the in situ software (reference [2]) (forced to a certain range and not taken into account in the parameter identification)
v_{fit}	[ms^{-1}]	Wind velocity over the collector as used in the in situ software (reference [2]) (varied, and the wind dependence of the collector losses is determined)
$(\alpha\tau)$	[-]	Effective transmittance-absorptance product of the collector
ΔT_{off}	[K]	Temperature difference for deactivating the collector loop pump
ΔT_{on}	[K]	Temperature difference for activating the collector loop pump
β	[rad]	Collector tilt angle
γ	[rad]	Collector azimuth angle
$\rho_w(T_S)$	[kg/l]	Density of water at temperature T_S
θ	[rad]	Angle of incidence
τ_F	[s]	Filter time constant

5 Apparatus

5.1 Mounting and location of the SDHW system

5.1.1 System mounting

The requirements for mounting and location are consistent with ISO 9459-2. The complete system shall be mounted in accordance with the manufacturer's guidelines. Whenever possible, the system shall be mounted on the mounting structure provided by the manufacturer. If no mounting is provided, then, unless otherwise specified (e.g., when the system is part of an integrated roof array), an open mounting system shall be used. Such mounting shall not obstruct the aperture of collectors and shall not significantly affect the back or side insulation of the collectors or the storage tank. Mounting shall be able to withstand the effects of wind gusts.

5.1.2 Collectors

5.1.2.1 Collector location

If collectors designed for integration into a roof have their underside protected from the wind, this shall be reported with the test results. In this case, the underside heat-loss coefficient of the collector test-rig shall be set in accordance with the manufacturer's guidelines, or shall have a value of $0,35 \pm 0,05\ Wm^{-2}K^{-1}$ if not prescribed by the manufacturer.

The height between the lower edge of the collectors and the ground of the test-rig shall be a minimum of 50 cm, unless specified otherwise by the manufacturer. Natural ventilation of the collector surface shall not be restricted by the mounting.

The temperature of surfaces adjacent to the system shall be as close as possible to that of the ambient air, in order to minimize the influence of thermal radiation. For example, the field of view of the system shall not include chimneys, cooling towers or hot exhausts. Warm currents of air, such as those that rise up the walls of buildings, shall not be allowed to pass over the system. Collectors mounted on the roof of a building should be located at least 2 m away from the edge of the roof.

5.1.2.2 Collector azimuth orientation

The collectors shall be mounted in a fixed position facing the equator to within ± 10°.

5.1.2.3 Collector tilt angle

The tilt angle shall remain constant throughout the test. The system shall be tested with the collector at a tilt angle within ± 5° of the latitude of the test site, unless otherwise specified by the manufacturer. This shall be reported with the test results.

5.1.2.4 Shading of collectors from direct solar irradiance

The collector shall be positioned in such a manner that no significant shadows of any object, other than the collector itself, will be cast into the collector aperture at any time during the test period.

5.1.2.5 Diffuse and reflected solar irradiance on collector plane

The collector shall be located where there will be no significant direct solar radiation reflected into it from surrounding buildings or surfaces during the tests, and where there will be no significant obstructions in the field of view.

With some collectors, such as evacuated tubular collectors, reflections onto both the back and the front of the collector shall be minimized. Not more than 5 % of the collector's field of view of the sky shall be obstructed, and it is particularly important to avoid buildings or large obstructions subtending an angle of greater than 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 testing. It is recommended that surfaces in the collector's field of view, that include large expanses of glass, metal, snow or water, be avoided.

5.1.2.6 Heat transfer fluid

The heat transfer fluid used in the system during testing shall be the fluid recommended by the manufacturer. The fluid used shall be reported. For all systems, the fluid flow rate resulting from system operation, as recommended by the manufacturer, shall be used.

5.1.2.7 Controller

Any controller included in the collector loop shall be set in accordance with the manufacturer's instructions. If no instructions are given, ΔT_{on} shall be set to 7 K. ΔT_{off}, if adjustable, should be set to 2 K. The controller setting shall be stated clearly in the test report.

5.1.3 Storage

5.1.3.1 Storage-tank location

The store shall be installed as specified in the manufacturer's installation instructions.

5.1.3.2 Storage ambient conditions

The store shall be mounted in a way that there is a uniform ambient air temperature in its vicinity.

Storage tanks separated from the collector array shall be situated in a closed room, taking into account the requirements regarding pipe length as stated in 5.1.4 and the manufacturer's instructions. The ambient temperature of the store shall be in accordance with 6.2.3.

5.1.4 Piping and insulation

The total length of the connecting pipes between the collector and the store shall be the longest length allowed by the published installation instructions for the systems. In the absence of such instructions, the total pipe length shall be 15 m ± 0,1 m. This piping shall be placed in such a way that the environment of the piping will be the same as for the store, as far as possible, in order to increase the reproducibility of the test results. The pipe length (total, length indoors and length outdoors) used shall be stated in the test report.

The diameter and insulation of the pipes shall be in accordance with the manufacturer's installation instructions. If not prescribed by the manufacturer, the pipe diameter and the insulation shall be chosen according to common installation practice and the pipe diameter and insulation used shall be stated in the test report. All pipes and pipe connections additional to the system under test shall be properly insulated, so that thermal losses are minimized.

5.1.5 Auxiliary heating

5.1.5.1 Integrated auxiliary heating

Integrated auxiliary heating can be provided either by a heat exchanger or an immersed electrical or gas heater. All parts of the integrated auxiliary heater that are located outside the store, the demand heater and all accompanying pipes shall be properly insulated so that thermal losses are minimized, and the measured energy corresponds to the actual auxiliary energy supply.

5.1.5.1.1 Heat exchanger

To avoid reverse thermosiphonic convection for auxiliary heating provided by a heat exchanger, the auxiliary heater shall be below the heat exchanger, or the pipes between the auxiliary heater and the heat exchanger shall have a downward bend of at least 300 mm deep, as close to the store as possible.

If a heat exchanger driven by a non-electrical heat source is used, a thermostatically controlled electrical water heater can be mounted as a by-pass to the non-electrical heater and can be used as the only auxiliary heat source during the test. The nominal power of this electrical demand heater shall be consistent with the rating of the boiler, if specified; or 100 W ± 30 W per litre of store volume above the lowest part of the heat exchanger. The power rating of the electrical demand heater used shall be reported.

5.1.5.1.2 Immersed heater

If an immersed heater is used, the heater delivered with the system shall be used. If no such heater is delivered with the system, a heater with a nominal power consistent with the rating of the immersed heater, if specified; or 25 ± 8 W per litre of store volume above the lowest part of the heater, shall be used. The actual power used shall be reported.

5.1.5.2 External auxiliary heating

Systems with external auxiliary heating shall be tested without auxiliary heating. The hot-water temperature sensor, and the volume flow-meter if mounted in the hot-water outlet line, shall be mounted between the storage tank and the external auxiliary heater.

All parts of the external auxiliary heater, that are located outside the store, the demand heater and all accompanying pipes, shall be properly insulated so that thermal losses are minimized, and the measured energy corresponds to the actual auxiliary energy supply.

5.1.6 Mixing valve

If a thermostatic mixing valve for limiting the outlet temperature is a part of the system, it shall be removed or disabled during the test.

5.2 Test facility

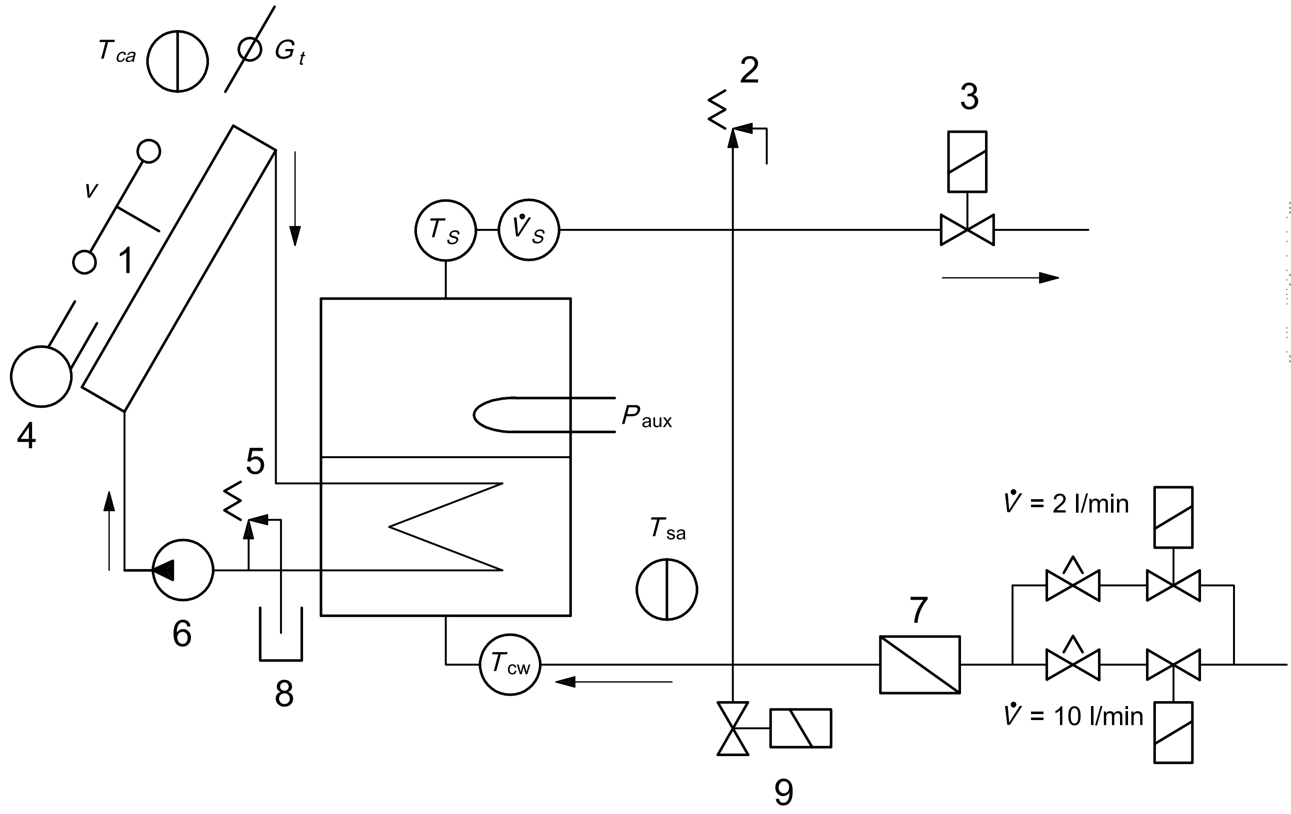
5.2.1 Measurement schematic

A typical measurement schematic for a system with forced circulation flow in the collector loop, and with an indoor store equipped with electrical auxiliary heating is shown in Figure 1. For different systems, the measurement points remain the same but the plumbing layout may vary as appropriate.

5.2.2 Piping

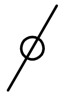
The piping used in the load loop shall be resistant to corrosion and suitable for operation at temperatures up to 95 °C. Pipe lengths in the load loop shall be kept short. In particular, the piping between the mains source of water with constant temperature and the inlet to the storage tank shall be minimized, in order to reduce the effects of the environment on the water-inlet temperature. The mains-water temperature is specified in 6.2.1.

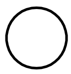
If a pipe with substantial length, which is in thermal contact with ambient air, leads from the mains-water supply to the storage tank, it is recommended to flush this part of the piping immediately before each draw-off in order to provide a constant mains-water temperature.

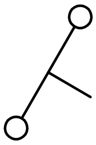


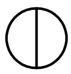
Key

1 collector
2 safety valve
3 draw-off valve
4 fan
5 safety valve
6 pump
7 non-return valve
8 expansion vessel
9 rinse valve

 = Pyranometer

 = Fluid thermometer (T) or flow meter ($\dot{V}$)

 = Anemometer

 = Air thermometer

NOTE See 5.4.5 for an alternative location of the flow-meter

Figure 1 — Typical test facility for a system with forced circulation of fluid in the collector loop and storage tank equipped with an immersed electrical auxiliary heater

Piping between the temperature-sensing points and the store (inlet and outlet) shall be protected with insulation and reflective weather-proof covers extending beyond the positions of the temperature sensors, such that the calculated temperature gain or loss along either pipe does not exceed 0,01 K under test conditions. This is assured if the pipe heat loss does not exceed 0,15 W/K for each pipe.

The facility shall allow continuous operation of the SDHW system and measuring of its performance under natural climatic conditions over a measurement period of several weeks, and shall fulfil all the requirements specified in Clause 6.

5.3 Instrumentation

5.3.1 Solar radiation measurement

A pyranometer shall be used to measure the solar irradiance. The pyranometer shall have characteristics in accordance with Class II of WMO classification and ISO 9060.

The pyranometer shall be calibrated using a standard pyrheliometer, in accordance with ISO 9060 and ISO 9846.

5.3.2 Temperature measurement

The accuracy and repeatability of the instruments, including their associated readout devices, shall be within the limits given in Table 1. The time constant (time required for 63,2 % response to a step change) shall be less than 3 s for sensors measuring fluid temperatures.

Table 1 — Temperature measurement accuracy

Parameter	Measurement accuracy
Temperature, ambient air	± 0,5 K
Temperature, cold-water inlet	± 0,3 K
Temperature difference across system (cold water into hot water out)	± 0,1 K or 1 % whichever is higher

NOTE For short draw-offs, the thermal inertia of temperature sensors may become the primary power-measurement error source. The use of slowly opening valves may greatly reduce this systematic power error.

5.3.3 Volumetric draw-off rate measurements

The accuracy of the volumetric draw-off rate measurement shall be equal to or better than ± 1,0 %.

5.3.4 Electrical energy

The electrical energy used shall be measured with an accuracy of ± 1,0 % of the reading or ± 15 W·h, whichever is greater.

5.3.5 Elapsed time

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

5.3.6 Surrounding air velocity

The surrounding air velocity shall be measured with an instrument and associated data acquisition system that can determine hourly mean values of the surrounding air velocity to an accuracy of ± 0,5 $m{\cdot}s^{-1}$. The start velocity of the instrument shall be 0,5 $m{\cdot}s^{-1}$ or less.

5.4 Location of sensors

5.4.1 Pyranometer

The pyranometer shall be mounted and operated in accordance with ISO 9060. It shall be installed at the same tilt and azimuth as for the collector plane. It shall be installed near the upper part of the collector array.

5.4.2 Ambient air temperature of the collector

The ambient air transducer shall be shielded 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.

5.4.3 Ambient air temperature of the store

The ambient air temperature shall be measured using a shaded ventilated sampling device approximately 1 m above the ground, not closer than 1,5 m to the store and system components and not further away than 10 m from the store.

5.4.4 Temperature sensors for fluid temperatures

The measurement points for mains water and draw-off temperature shall be located as close as possible to the store. The piping between measurement points and the storage tank shall contain no more than 0,3 l of water each. The hot-water sensor shall be mounted close to the store, so that the store and transducer are thermally coupled even when there is no draw-off.

5.4.5 Volumetric flow-meter and flow control device

It is recommended to install the flow-meter directly adjacent to the draw-off temperature sensor as shown in Figure 1. If variations of the draw-off temperature influence the flow-meter accuracy such that it does not comply with the requirements of 5.3.3, it shall be installed in the mains-water pipe directly adjacent to the measurement point of the mains-water temperature and the mass flow rate adjusted for the change in density according to the formulas given in 6.3.2.

The mass flow rate at the store outlet equals the mass flow rate delivered to the user; therefore, the volume flow rate at the outlet should be measured and multiplied by the density of water at the current draw-off temperature to obtain the correct mass flow rate. However, if the flow-meter is not able to operate with sufficient accuracy over the wide range of temperatures occurring at the outlet, the volume flow rate may be measured at the store inlet. In this case, the draw-off capacity rate shall be corrected according to the formulas given in 6.3.2 and discussed in Annex D.

5.4.6 Anemometer

The surrounding air velocity shall be measured by an anemometer positioned at a height approximately equal to the height of the centre of the collector array. The anemometer should be situated within 1 m of the collector array. If a forced air flow over the collector is used, the anemometer shall be placed so that it measures the velocity of the air stream passing over the collector.

5.4.7 Additional sensors

Additional sensors may be installed in order to obtain data for characterization of components in parallel with the test sequences in this part of ISO 9457, provided that the normal functioning of the system is not influenced.

6 Test method

6.1 General

6.1.1 Fluid

The collector circuit and the store shall be filled with a fluid in accordance with the manufacturer's guidelines. If the manufacturer supplies the fluid for the collector circuit, its composition shall be checked by a density or refractive index measurement. No gas bubbles shall be present in the collector circuit. The system shall be checked for leakage at a pressure specified by the manufacturer, or at 0,6 MPa if no test pressure is specified. The system shall be checked to ensure that it does not lose energy due to reverse flow through the collectors. If reverse flow is a possibility, the heat loss shall be evaluated with and without the collector circuit isolated from the tank. Comparison of these two will indicate if reverse flow is occurring.

6.1.2 Glazing

The collector glazing and the pyranometer shall be kept clean during performance monitoring.

6.1.3 Auxiliary heating

The test procedure can be applied to systems with or without integrated and/or external auxiliary heating.

a) Integrated auxiliary heating shall be activated during the test in accordance with this clause.

b) External auxiliary heaters shall be disabled during the test. They are not considered to be part of the system being tested; see 5.1.5.2.

NOTE This part of ISO 9459 can be applied to systems that have integrated auxiliary heating in the form of an immersed gas heater, provided

— the efficiency of the immersed gas heater is adequately measured (if necessary, as a function of the temperature of the surrounding water),

— instead of the auxiliary heat, the gas consumption is measured during testing and converted to auxiliary heat input to the tank contents in the data records, and

— during performance predictions, the auxiliary heat demand is converted to a gas consumption.

6.2 Test conditions

6.2.1 Mains-water temperature

The mains-water temperature shall not differ by more than ± 10 K from the average ambient temperature of the store. During draw-offs, the mains-water temperature shall be between 5 °C and 25 °C for all test sequences. It shall be constant to within 3 K within each test sequence, and temperature changes shall be less than 2 K/h. Temperature peaks at the beginning of a draw-off, due to heat conduction from the store or the thermal inertia of the sensors, are allowed.

6.2.2 Air velocity surrounding the collectors

There are three different options concerning wind velocity in the vicinity of the collectors:

v_{ignore} The wind velocity is not used, but is recorded.

This shall not be used for systems with unglazed collectors.

v_{force} The wind velocity is forced to a certain range and not taken into account in the parameter identification.

The wind velocity over the collector plane shall be above 3 m/s during sequences **S-sol** and **S-store** for irradiance larger than 200 $W \cdot m^{-2}$.

If necessary, artificial wind generators shall be used (e.g. a cross-flow fan). The temperature of the air leaving the wind generator shall not differ by more than 1 K from the ambient air temperature.

This shall be used for systems with glazed collectors.

This shall not be used for systems with unglazed collectors.

v_{fit} The wind velocity is varied and the wind dependence of the collector losses is determined.

This is mandatory for systems with unglazed collectors.

The average surrounding air velocity parallel to the collector plane shall include the following two states:

a) exceeding 3 m/s for at least 2 days under **Test B** conditions (between 06:00 and 18:00) during sequence **S-sol**, and

b) below 1,5 m/s with the same requirements as in a).

If the natural air velocity is not sufficient, an artificial air velocity of 3 m/s to 5 m/s shall be generated by a suitable arrangement (see comments for option v_{force}) during the **Test B** days of measurement.

6.2.3 Ambient temperature of the store

For systems where the store is located indoors, the ambient temperature near the store shall be constant to within ± 5 K for each sequence. The location of the store shall be described in the test report.

6.2.4 Control of the auxiliary heating

Control of the integrated auxiliary heating shall be activated or disabled as specified in 6.3.3. The temperature set point shall be as specified by the manufacturer, or (55 ± 5) °C if it is not specified. For sequences where the maximum temperatures specified in 6.3.3 are applied, the set temperature shall be the minimum of that specified by the manufacturer, or the threshold temperature minus 5 K.

The dead band temperature difference, if adjustable, shall be (5 ± 2) K. The internal auxiliary time control should be deactivated during testing, i.e. the auxiliary time control shall be controlled by the operator. If deactivation is not possible, this shall be stated in the report.

6.2.5 Conditioning

The conditioning at the beginning is intended to provide a well-defined initial system state, i.e. temperature profile in the store. The conditioning at the end is intended to evaluate the energy and the temperature profile contained in the system. The time after which the initial state has no further influence on the current state is called the skip time, Δt_{skip}, and the skip time Δt_{skip} shall be set to the length of the preconditioning phase.

At the beginning and at the end of each test sequence, the store is brought to uniform temperature by applying a draw-off rate of (10 ± 1) l min^{-1}. If the system was not designed to yield 10 l/min, the maximal design flow-rate shall be used. This shall be reported. Conditioning takes place during the night, or with covered collector surface and pyranometer domes. Integrated auxiliary heating shall be disabled during conditioning.

At the beginning of each sequence, at least three store volumes shall be withdrawn.

At the end of each sequence, final conditioning is recommended until either three store volumes are withdrawn or the difference between the store outlet temperature and the mains-water temperature is less than 1 K.

NOTE Final conditioning of a test sequence may be used as the starting conditioning of another sequence.

6.3 Test sequences

6.3.1 General

A test consists of several test sequences, called **S-sol, S-store** and **S-aux**:

S-sol: A test sequence containing a number of consecutive days of measurement with significant solar input. It shall be carried out in accordance with a test sequence time schedule based on two specific daily operation conditions named **Test A** and **Test B,** as described in 6.3.2 and 6.3.3. The daily tests take into account system specific dimensions, i.e. store volume and collector array area and/or actual draw-off temperature.

S-store: Store-loss test sequence.

S-aux: A test of the operation of the system with an integrated auxiliary heater under low solar irradiation conditions.

6.3.2 Test A

The aim of Test A days is to acquire information about collector array performance at high efficiencies. The draw-offs specified are designed to keep the collector inlet cold.

The integrated auxiliary heater (if present) shall be disabled for Test A days.

The draw-off profile consists of draw-offs starting at the times specified in Table 2. Here, t_0 denotes the actual start time of the first draw-off of the day. t_0 shall be between 6:30 and 8:00 solar time.

Table 2 — Draw-off start times for test A

Draw-off No.	Draw-off start time
1	t_0
2	t_0 + 2 h ± 5 min
3	t_0 + 4 h ± 5 min
4	t_0 + 5 h ± 5 min
5	t_0 + 6 h ± 5 min
6	t_0 + 8 h ± 5 min
7	t_0 + 11 h ± 5 min

For test facilities intending to test several systems simultaneously with only one mains-water pipe (where draw-offs shall take place one after another to meet the flow-rate requirements), the draw-off profile is intended to allow maximum flexibility for draw-off starting times, while keeping strict intervals between draw-offs to avoid overheating. The exact start time of the first draw-off is allowed to vary while the intervals between draw-offs shall follow the sequence specified in Table 3.

The draw-off volume flow rate shall be (10 ± 1,0) l min^{-1}. However, a flow rate of (2 ± 0,5) l min^{-1} during the first minute of each draw-off is recommended, in order to reduce measurement errors due to the thermal inertia of sensors. The mains-water temperature shall be selected in accordance with 6.2.1.

The volume of each draw-off for **Test A** depends on the system dimensions as specified in Table 3. However, the volume of any draw-off shall not be less than 20 l.

Table 3 — Draw-off volumes for test A

System dimensions	Draw-off volume
$100\ \text{l m}^{-2} \leqslant V_S/A_C \leqslant 200\ \text{l m}^{-2}$	$0{,}2\ V_S \pm 10\ \%$
$60\ \text{l m}^{-2} \leqslant V_S/A_C \leqslant 100\ \text{l m}^{-2}$	$0{,}25\ V_S \pm 10\ \%$
$40\ \text{l m}^{-2} \leqslant V_S/A_C \leqslant 60\ \text{l m}^{-2}$	$0{,}33\ V_S \pm 10\ \%$
$20\ \text{l m}^{-2} \leqslant V_S/A_C \leqslant 40\ \text{l m}^{-2}$	$0{,}5\ V_S \pm 10\ \%$

For a **Test A** day to be valid, the irradiation in the collector plane shall exceed 12 $\text{MJ}\cdot\text{m}^{-2}$.

6.3.2.1 Under-dimensioned storage tank

If system dimensions are in the range $10\ \text{l m}^{-2} \leqslant V_S/A_C \leqslant 20\ \text{l m}^{-2}$, 12 draw-offs of $1{,}0\ V_S \pm 10\ \%$ each shall be drawn, starting between 6:00 and 7:00 solar time, with intervals of 1 h ± 5 min.

6.3.3 Test B

The aim of this test is to acquire information about store heat losses and collector array performance at low efficiencies. The draw-offs specified for **Test B** days are designed to allow the system to become as hot as possible for as long as possible, while avoiding overheating of the store.

The integrated auxiliary heater (if present) shall be **enabled** at, or not more than, 1 h after the end of the last draw-off of each **Test B** day, and **disabled** at, or not more than, 1 h before starting the first draw-off of each **Test B** day. If the manufacturer specifies that the auxiliary heater is not to be switched off during the day then the system shall be operated as specified. This shall be stated in the report. The set point of the auxiliary heater shall be adjusted as specified in 6.2.4.

The draw-off profile consists of five draw-offs starting at the times specified in Table 4. Again, t_0 denotes the actual start time of the first draw-off of the day. t_0 shall be between 8:30 and 10:00 solar time.

Table 4 — Draw-off start times for test B

Draw-off No.	Draw-off start time
1	t_0
2	t_0 + 2 h ± 5 min
3	t_0 + 4 h ± 5 min
4	t_0 + 6 h ± 5 min
5	t_0 + 8 h ± 5 min

The draw-off volume flow rate shall be (2 ± 0,5) l min^{-1} during at least the first minute of each draw-off. Afterwards, the draw-off rate may be raised to (10 ± 1) l min^{-1}. The mains-water temperature for sequences **S-sol** shall be taken in accordance with 6.2.1.

Draw-off volumes for **Test B** days depend on the system dimensions and draw-off temperature. The system is prevented from boiling or activating overheat protection by withdrawing in the following way. For each draw-off, at least 5 l shall be drawn. The draw-off shall be continued as long as the measured store outlet temperature during the draw-off is greater than the required threshold temperature, or a maximum volume has been reached. The draw-off shall end when

— at least 5 l have been withdrawn, and

— either 20 % of V_S (for the range 20 l/m^2 ⩽ V_S/A_C ⩽ 40 l/m^2, 40 % of V_S) has been withdrawn, or the outlet temperature drops below the threshold temperature.

The threshold temperature shall be chosen in accordance with Table 5:

Table 5 — Threshold temperatures for Test B days

System dimensions	Temperature
100 l m^{-2} ⩽ V_S/A_C ⩽ 200 l m^{-2}	70 °C
60 l m^{-2} ⩽ V_S/A_C ⩽ 100 l m^{-2}	60 °C
40 l m^{-2} ⩽ V_S/A_C ⩽ 60 l m^{-2}	50 °C
20 l m^{-2} ⩽ V_S/A_C ⩽ 40 l m^{-2}	40 °C

If the overheating protection mechanism is activated during the test due to high temperatures in the store, during **S-sol, B** days, the **S-sol, B** sequence should be repeated with a lower threshold temperature. If a lower threshold is used, it shall be reported.

If the set point of an integrated auxiliary heating cannot be changed, the threshold temperature shall be chosen to be at least 5 K higher than the set point of the integrated auxiliary heating.

For a **Test B** day to be valid, the irradiation in the collector plane shall exceed 12 MJ m^{-2} during this day. If the temperature of the water withdrawn in a **S-sol, B** sequence is always below the threshold temperature, the sequence shall be extended until two consecutive days with irradiation of 15 MJ/m^2 or greater are included.

6.3.3.1 Under-dimensioned storage tank

If system dimensions are in the range 10 l/m^2 ⩽ V_S/A_C ⩽ 20 l/m^2, 12 draw-offs shall take place, starting between 6 a.m. and 7 a.m., with intervals of 1 h ± 5 min. Each draw-off volume shall be not less than 5 litres, and each draw-off shall be continued as long as the draw-off temperature exceeds a threshold temperature of 40 °C.

6.3.4 Test sequence with solar input S-sol

The sequence shall be prolonged until the following requirements are fulfilled.

— A minimum of three valid days under **Test A** conditions are recorded, and three valid days under **Test B** conditions are recorded.

— Of the valid **Test B** days, at least two shall be consecutive.

— Within each sequence or sub-sequence (see below), the number of valid **Test A** days shall be at least one-third of the total number of **Test A** days and the number of valid **Test B** days shall be at least one-third of the total number of **Test B** days.

— The total number of valid **Test A** days, if more than four, shall not be greater than the total number of valid **Test B** days, and shall not be less than the total number of valid **Test B** days minus two.

The data for this sequence need not necessarily be taken from a single continuous test sequence (e.g., it may be split in two sub-sequences with **Test A** and **Test B** days, respectively). The data of all sub-sequences shall then be used simultaneously for parameter identification. However, each sub-sequence shall start with a conditioning period. The skip time shall be set accordingly for each sub-sequence, and the data from each sub-sequence shall be contained in one continuous data file.

6.3.5 Store-loss test sequence, S-store

This sequence is intended to identify the overall store losses. It consists of four phases:

a) Conditioning in accordance with 6.2.5.

b) Heating up the store: requires two consecutive valid **Test B** days (without auxiliary).

c) Cooling period: takes 36 to 48 h starting from the last draw-off of the heating period. During the cooling period there shall be no draw-off and low solar irradiance. If solar irradiance higher than 200 Wm^{-2} is expected, solar energy input into the store shall be avoided by one of the following measures.

   — A radiative shield at a temperature of at maximum 5 K above ambient shall be placed in front of the collectors. The pyranometer dome shall also be covered. Alternatively, its measured output can be set to zero.

   — For systems where the store may have radiation losses to the sky, it is recommended to place the shield at some distance above the collector aperture, in order to shield direct radiation while leaving the collector open to most of the long-wave sky radiation effects.

   — For forced-circulation systems, the circulation in the collector loop shall be stopped (e.g., by closing a valve and disabling pump operation). The measured output of the pyranometer and the collector ambient-temperature sensor shall be set to zero. This method may only be applied, if it is ensured that no thermosiphonic flows leading to store heat losses occur in the collector loop when the pump is off. No valve shall be included in the collector loop for this purpose only.

d) Final conditioning in accordance with 6.2.5.

If there is a possibility to control the air temperature in the vicinity of the store, the lowest possible temperature should be chosen during the whole sequence.

6.3.6 Auxiliary test sequence S-aux

This sequence is intended to determine the heat losses and the volume fraction of the auxiliary heated portion of the store. The operation of systems with an integrated auxiliary heater under low solar irradiation is assessed. After conditioning in accordance with 6.2.5, four **Test B** days are required. Solar radiation shall be below 200 W m^{-2}, or artificially kept low as described for sequence **S-store**. The auxiliary heater shall be enabled from $t_0 + 9$ h to $t_0 + 23$ h and disabled at all other times. If the manufacturer specifies that the auxiliary heater is not to be switched off during the day, the system shall be operated as specified. This shall be stated in the report. The setpoint of the auxiliary heater shall be adjusted as specified in 6.2.4.

6.4 Data acquisition and processing

6.4.1 General

During measurement of the system being tested, the data specified in Table 6 have to be measured and recorded by the data logger. For the purposes of this Clause, *sampling* means taking one instantaneous measurement of a physical quantity, and *recording* means writing a value derived from one or more sampled values to the result file.

6.4.2 Data sampling

All measured data during a test sequence shall be sampled with time intervals not exceeding the values specified in Table 6.

If the draw-offs are controlled by the measuring program, it is recommended to use a new sampling interval from the beginning of each draw-off period (see 6.4.3). An integrating measuring device should be used for draw-off and auxiliary energy.

Table 6 — Maximum sampling intervals of the measured variables

Symbol	Unit	Variable	Maximum sampling interval	
			Draw-off	No draw-off
T_{cw}	[°C]	Mains-water temperature	2 s [a]	30 s
T_S	[°C]	Store outlet temperature	2 s [a]	30 s
$\dot{V}_S$	[l/min]	Volumetric draw-off rate	2 s [a]	30 s
P_{aux}	[W]	Auxiliary power	2 s [a]	30 s
G_t	[W·m^{-2}]	Hemispherical irradiance	5 s	5 s
T_{ca}	[°C]	Collector ambient air temperature	30 s	30 s
T_{sa}	[°C]	Storage-tank ambient air temperature	30 s	30 s
v	[m·s^{-1}]	Surrounding air velocity	30 s	30 s

[a] If integrating instruments are used for measuring the draw-off rate and the auxiliary power, the maximum sampling intervals may be changed from 2 s to 5 s.

Sampling is required during no draw-off to check system operation.

6.4.3 Data processing

The sampled values shall be continuously integrated and averaged as specified in 6.4.4. In addition to measured variables that are used directly, the algorithm requires data on draw-off capacitance rate and draw-off load power.

a) For closed, non-pressurized systems, the volume flow rates at inlet and outlet are equal and the draw-off capacitance rate and draw-off power shall be calculated according to Equations (1) and (2), respectively.

$$\dot{C}_S = c_w\left(T_{cw}, T_S\right)\rho_w\left(T_S\right)\dot{V}_S \tag{1}$$

$$P_L = \dot{C}_S\left(T_S - T_{cw}\right) \tag{2}$$

b) However, if the volumetric flow-meter is installed in the mains pipe instead of the draw-off pipe, the difference between the mass flow rates at the store inlet and outlet shall be taken into account. The mass flow rates at the store inlet and outlet may differ, due to the thermal expansion of water or due to changes in the water pressure (see D.2.2). If the mass flow rates at inlet and outlet are equal, or the integral of the mass flows are equal, the draw-off capacitance rate and draw-off power shall be computed according to Equations (3) and (4). This would be the case, for example, for a store with a one-way valve and an expansion vessel.

$$\dot{C}_S = c_w\left(T_{cw}, T_S\right)\rho_{cw}\left(T_{cw}\right)\dot{V}_S \tag{3}$$

$$P_L = \dot{C}_S\left(T_S - T_{cw}\right) \tag{4}$$

If it is not clear which case is applicable, Equations (1) and (2) shall be used. If auxiliary heating is provided by a heat exchanger, P_{aux} shall be measured in the same way as P_L, in most cases in accordance with method b) of this subclause. The recorded time shall describe the time at the end of the measurement interval, which started at the end of the previous record.

NOTE The temperature dependence of the specific heat and density of water are given in Annex D, as well as a detailed discussion of the computation of capacitance rates and thermal powers.

All derived variables shall be computed directly when measured for each set of sampled values.

6.4.4 Data recording

The averaged values for each variable shall be computed over a recording interval and stored. Maximum recording intervals are 30 s during draw-offs, commencing at the start of each draw-off, and 5 min elsewhere. The measurement interval shall be synchronized to begin at the start of a whole recording interval after the start of a sequence or sub-sequence. The data recording interval may vary during the measurement sequence. The data in any sequence or sub-sequence shall be continuous, whereas sequences or sub-sequences may be discontinuous.

Annex D contains recommendations for hardware and data acquisition software, as well as an explanation for the equations given in 6.4.3.

7 Identification of system parameters

7.1 Dynamic fitting algorithm

When all the requirements of Clause 6 are fulfilled, identification of system parameters shall be carried out using the dynamic fitting algorithm as described in Annex A, with the data of all measured test sequences. The model specified in Annex A shall be used.

7.2 Options

The following options within the software model (see Annex A) shall be enabled [turned on] for the identification of system parameters:

`WindCollector`: Shall be used for option v_{fit} only (see 6.2.2). The collector loss coefficient u^*_C depends linearly on the wind velocity over the collector plane.

`DrawoffMix`: Shall be used when draw-off causes significant mixing within the store.

`SolarStratification`: Shall be used when solar loop operation may generate significant stratification.

`Aux`: Only for systems with an integrated auxiliary heater.

`LoadHeatExchanger`: Only for systems with a load-side heat exchanger.

Additional parameter identifications with different option settings may be carried out as chosen by the test engineer; the corresponding results should then be appended to the test report.

7.3 Constants

The filter time constant τ_F should be set to 4 h. The draw-off related filter constant C_F (in J/K) should be set to 400 times the store volume V_S, in litres (which makes $C_F \pm 0,1\ C_S$).

7.4 Skip time

The skip time for each data file shall be set corresponding to 6.2.5, i.e. to the time used for the conditioning at the beginning.

7.5 Parameters

The results from parameter identification should encompass the parameter values, as well as a covariance matrix. The model options used have to be transferred to the algorithms for long-term performance prediction. Parameters shall not be fixed.

Zero variance of the parameters will be indicated by

— a singular covariance matrix caused by insufficient variability of the input data, in combination with the parameters to be determined, or

— erroneous fixing of one or more parameters.

Data with a singular covariance matrix shall be rejected.

8 Performance prediction

8.1 Yearly performance prediction and reporting

The yearly performance Q_{net} of the system shall be predicted, in accordance with the method outlined in Annex A, and reported using the reporting format given in Annex C. If the system fails to meet the required temperature demanded by the user (T_D) for certain loads, this shall be reported together with the performance test results.

8.2 Reference conditions

Recommendations for reference conditions are given in C.2.3 and C.2.4.

Annex A
(normative)

Basis of dynamic SDHW system testing

A.1 Introduction

This annex provides a brief description of short-term SDHW systems testing. A more detailed explanation of the method can be found in references [1], [3], [4], [5], [6].

There are two aspects that must be accounted for in modelling the performance of an SDHW system: First, the gain of an SDHW system depends on a wide range of factors, such as solar irradiance, ambient temperature, load volume and profile and cold-water temperature. Second, the 'system time constant', for example, the time in which one store volume is withdrawn, is often longer than one day.

Consequently, several parameters have to be determined to characterize the influence of various effects on the system under test, and the time taken to establish each parameter may be several multiples of the system time constant. If a steady-state is required, that is: the energy in the store as well as its vertical temperature profile has to be equal at the beginning and the end of the sequence, several months of testing may be required.

The method used in this part of ISO 9459, the dynamic method[3)], aims to minimize experimental effort by the use of mathematical tools, which extract as much information as possible from the test data. Additionally, there is no requirement to attain steady-state, which also reduces the time needed, because it may take more time to achieve steady-state than to vary input variables for determination of one parameter.

The method uses the data derived from a short-term test to predict the long-term performance of the system under test for different conditions. For this, parameters in a SDHW model are fitted to the test data, and the model, in conjunction with the values of the parameters found, is applied to the prediction conditions.

The method was developed to meet the following objectives.

- Testing can be carried out in indoor or outdoor test facilities and in situ.
- It is a black-box test, i.e. there is no requirement to measure data within the system (e.g. inside the store).
- The test can be undertaken in a short time period.
- Low cost.
- Prediction possible for any meteorological and load conditions.
- Applicable to a large class of systems.

NOTE 1 So far, a rather simple SDHW system model has been used, which is nevertheless applicable to a large number of today's systems available on the market place. For more sophisticated SDHW systems, the simple model can be replaced accordingly, without changing the basic methodological features.

NOTE 2 The mathematical tools used in the method have been optimized to be robust enough to avoid being misled by unimportant transient effects.

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3) A program package complying with the requirements stated in Annex A is available from references [2] and [16].

A.1.1 Model options

The model includes the following options.

— **Aux:** Modelling of an auxiliary heater integrated in the store.

— **DrawoffMix:** Any draw-off is associated with mixing inside the store (parameter D_L).

— **LoadHeatExchanger:** A heat exchanger decoupling the store from the load loop is modelled by a parameter, the thermal resistance R_L of the heat exchanger.

— **SolarStratification:** This option can be used for systems which are capable of generating stratification by operation of the solar loop (e.g. for low-flow systems). The degree of stratification is described by the value of the parameter S_C.

— **WindCollector:** Models the wind velocity dependence of the collector losses, assuming u_C^* to depend linearly on v, $u_C^*(v) = u_C^*(0) + u_v \cdot v$.

A.1.2 Algorithm of parameter identification

The data-fitting procedure is used to identify the parameters. The method works by reversing the dynamic system simulation process: while simulation yields the system output from given parameters, dynamic fitting yields the parameters from the measured system gain.

A.1.3 Long-term performance prediction

The same model that was used for fitting shall be used for long-term prediction (LTP), with the following changes.

a) A thermostat mixer which reduces the load temperature T_L, from T_S to the (fixed) demand temperature T_D.

b) Collector loop operation is stopped for store temperatures exceeding 100 °C.

c) An auxiliary controller which keeps the auxiliary fraction of the store above a set temperature T_{set}, using up to the maximum auxiliary power $P_{max\ aux}$.

Although the same model shall be used, different climatic and load conditions may be used for performance predictions.

A.2 Benchmarking

A reference case is defined, in order to check whether a specific implementation of the SDHW system model and parameter-identification algorithm is compatible with the definitions outlined in this annex, and may be used for the purpose of this part of ISO 9459. The following procedure shall be followed in order to prove the compatibility of the specific implementation.

For the benchmark test, synthetic measured data for a solar domestic hot-water system are provided on a diskette from reference [16] (DIN). A description of the system model is given in Table A.1.

Table A.1 — Model parameters of the reference system

System:	forced-circulation type
Collector:	collector aperture area: 5 m^2 optical efficiency: $\eta_0 = 0{,}8$ collector heat-loss coefficients: $a_1 = 3{,}5$ W/(m^2K), $a_2 = 0{,}02$ W/(m^2K^2) collector heat capacity: 7 kJ/(m^2K) incident angle modifier coefficient: $K_{\tau\alpha}(50°) = 0{,}92$
Collector Loop:	flow-rate: 60 l/h (low flow) pump switch-points: $\Delta T_{on} = 10$ K, $\Delta T_{off} = 2$ K total pipe length: 30 m
Storage:	volume: 300 l storage capacity: 1,25 MJ/K heat-loss rate: 2,2 W/K storage ambient temperature: 15 °C effective vertical heat conductivity $2 \times \lambda_{water}$
Heat Exchanger: (Solar Loop)	mantle heat exchanger (stratified charging) $(UA)_{hx} = 543$ W/K (at mean fluid temperatures of 20 °C)
Auxiliary Heater:	immersed electric heating element, maximum heating power: 8 kW volume of auxiliary heated part: 135 l

The long-term performance prediction shall be carried out for the set of weather data of Wuerzburg and a daily load of 200 l/d. The fractional system gain shall be obtained in the range from 0,508 to 0,524.

The specific model and the parameter-identification implementation are considered as compatible with the definitions outlined in this annex, when the predicted long-term performance is within the specified range.

The synthetic measured data provided are not sufficient for checking the model options `WindCollector` and `LoadHeatExchanger`. In cases where these options are to be checked, it is recommended to generate synthetic data with a suitable simulation programme for solar domestic hot-water systems, and to follow the procedure as outlined above.

A.3 Nomenclature (specific for Annex A)

Symbol	**Units**	**Meaning**
$P_{max\ aux}$	[W]	Maximum auxiliary power available
T_L	[°C]	Temperature of the water delivered to the user ($T_L \leqslant T_S$)
T_D	[°C]	Temperature demanded by the user
T_{set}	[°C]	Set temperature of the auxiliary heater controller

Annex B
(normative)

Validation of the test method

B.1 Systems for which the method has been validated

a) Systems with forced circulation in the solar collector loop, with glazed flat plate collectors with collector heat-loss coefficients lower than $a_1 = 5$ W/(m^{2}K), $a_2 = 0{,}04$ W/(m^{2}K^2) and with an incident angle dependency for solar irradiance limited by the following equation: $K_{\tau\alpha} = 1 - [\tan(\theta/2)]^{1/r}$ with $r < 0{,}4$. Note that test data for systems with higher incident-angle dependency may be processed using corrected solar irradiance [see footnote 1) in Clause 1].

b) Systems with forced circulation in the solar collector loop, with ETC collectors with direct fluid flow in the absorber.

c) Systems with forced circulation in the solar collector loop, with ETC heat pipe collectors for which dry-out does not occur during testing and during normal operation.

For these system types, validation of the method has been carried out (references [17], [18]).

NOTE The list in this clause resembles the state-of-the-art in February 1995. It is expected to grow due to further validation of the method (proposal to the European Programme on Standardization, Measurements and Testing). In a few years, the method is expected to be validated for all system types indicated in Clause 1.

B.2 Procedure for systems for which the method has not been validated

For systems not included in B.1 and for which previous validation has not taken place, both the range of test conditions and the data processing model shall be validated as well. In this case, the test procedure includes validation and consists of the following steps:

a) Performance of two full dynamic tests as described in Clause 6. The tests shall be carried out in periods in which specific system characteristics different from the data processing model (see Annex A) are most exposed in different directions.

   For instance, the two tests for systems with strong temperature dependency of the collector loop heat loss shall be performed first in a period with a relatively low, and then in a period with a relatively high, ambient air temperature.

b) Evaluation of the two dynamic tests into annual performance predictions for all required meteorological and load conditions.

c) The net system gain Q_{net} from the two tests shall vary by less than 5 % for all three climates of the table in C.2.3 for the design load of the system. The design load shall have been chosen beforehand by the manufacturer from the loads in the table in C.2.3. If no design load is specified, a load from the table in C.2.3 between 0,5 and 1 times the store volume shall be chosen.

d) If validation of the method under c) is positive, test data of both tests shall be combined and used for the annual performance prediction to be presented in the test report.

Annex C
(normative)

Test report

TESTING LABORATORY: ....

ADDRESS:	....
	....
TEL:	....
FAX:	....
E-MAIL:	....
DATE OF ISSUE:	....

C.1 Description of the system

C.1.1 Name and address of manufacturer:
....

....

....

C.1.2 System model:
....

Serial Number: ....

C.1.3 System Classification

- Thermosyphon .... forced ....
- Direct .... indirect ....
- Open .... vented .... closed ....
- Filled .... drainback .... draindown ....
- Remote storage .... close-coupled collector storage ....
- Integral collector storage ....
- Other (specify) ....

C.1.4 Heat transfer medium

- Type: .... water .... oil .... freon .... air

.... water-ethylene glycol mixture, concentration of glycol .... %

.... water-propylene glycol mixture, concentration of glycol .... %

.... other (specify) ....

- Specifications: ....

- Total medium content: .... kg

C.1.5 Antifreeze protection (other) ....

C.1.6 Number of collector modules ....

and total collector gross area ....

C.1.7 Collector

- Type: flat plate .... evacuated tube ....

other (specify) ....

- Gross area: .... m^2

- Aperture area: .... m^2

- Number of covers: ....

- Cover material(s): ....

- Cover thickness(es): ....

- Insulation material(s): ....

- Insulation thickness: ....

- Casing material: ....

- Weight of collector without fluid: ....

- Gross dimensions: ....

C.1.8 Absorber

- Material(s): ....

- Construction: ....

- Surface treatment: ....

- Number of tubes/channels: ....

- Diameters: ....

- Distances: ....

- Area: .... m^2

C.1.9 Storage tank

- Type: ....
- Volume: l
- Outside diameter: ....
- Insulation material ....
- Insulation thickness ....
- Heat exchanger(s): ....

.... mantle .... helix .... external heat exchanger

C.1.10 Pump

- Type: ....
- Electrical power (for recommended settings) .... W

C.1.11 Controller

- Type ....
- Controller Settings ....

....

....

....

C.1.12 Schematic diagram of the hydraulic system

NOTE This page is a placeholder for the schematic diagram of the actual system under test and is intentionally left blank.

C.1.13 Connecting piping between the collector(s) and the tank

- Diameter ....
- Length ....
- Insulation material ....
- Insulation thickness ....

C.1.14 System data

- Tilt angle of collector support .... Tilted roof collector ....
- Location of heat store: Indoors .... Outdoors ....
- Collector loop flow rate ....
- Controller setting ....

....

....

C.1.15 Comments on system design

....

....

C.2 System performance test

C.2.1 Description of Measured Data

Sequence number	1	2	3	4	5	6
File name on disk						
Sequence type (S-sol, S-aux, S-store)						
Number of days						
Number of A days Number of valid A days						
Number of B days Number of valid B days						

C.2.2 System parameters

Parameter	Symbol	Value	Unit
Effective collector area	A_C^*		m^2
Effective collector loss coefficient	u_C^*		$Wm^{-1}K^{-1}$
Total store heat-loss coefficient	U_S		W/K
Total store heat capacity	C_S		MJ/K
Fraction of the store used for auxiliary heating	f_{aux}		-
Mixing constant	D_L		-
Stratification parameter	S_C		-
Thermal resistance of load heat exchanger	R_L		10^{-3} K/W
Wind speed dependence of u_C^*	u_v		$Jm^{-3}K^{-1}$

Wind option used: .... W_{ignore} .... W_{force} .... W_{fit}

Correction used: ....

....

C.2.3 Performance for standard conditions

NOTE It is up to national or regional standards bodies to specify reference weather data and reference conditions to be used for performance predictions. Recommendations for reference conditions are given in C.2.4.

Climate	Location (latitude)
Load l/day*	Q_{net} MJ/a
50	
70	
100	
150	
200	
300	
500	
700	
1 000	
1 500	
*: From the loads mentioned here, only those loads considered relevant for the system may be used.	

C.2.4 Reference conditions for performance prediction

Reference condition	Value	Recommended Value
Tilt angle of the collector		Latitude
Orientation of the collector		Facing the equator
Daily draw-off rate		10 l/min
Draw-off 1 (volume, time)		40 %, 07:00
Draw-off 2 (volume, time)		20 %, 12:00
Draw-off 3 (volume, time)		40 %, 19:00
Desired draw-off temperature T_D (if this temperature is exceeded, mains water is mixed to achieve T_D)		45 °C
Mains-water temperature T_{cw}		10 °C
Ambient temperature of the store T_{sa} (if not equal to T_{ca})		15 °C
Auxiliary power $P_{aux\ max}$		
Auxiliary set temperature T_{set}		60 °C
Auxiliary heater timer control		Switched on continuously

C.2.5 Remarks

....

....

....

....

....

....

Annex D
(informative)

Hardware and software recommendations

D.1 Hardware recommendations

The following set of instruments and sensors is recommended for solar domestic hot-water (SDHW) systems:

- *Irradiance:* Class 1 pyranometer as specified in ISO 9060.
- *Collector ambient temperature:* Ventilated, double-shielded resistance-temperature-detector (RTD) thermometer or calibrated Ics thermocouples.
- *Store ambient temperature:* Standard RTD thermometer or thermocouples.
- *Wind velocity:* Cup anemometer or ultrasonic anemometer.
- *Fluid temperature:* Very short response time four-wire Pt100 RTD in stainless steel tube.
- *Volume flow:* Piston ring flow-meter or magnetic-inductive flow-meter.
- *Electrical power:* Commercial electricity meter with electrical pulse output.

D.2 Measuring the thermal energy drawn from a hot-water store

This clause covers the following items.,

- A definition of the *thermal power* P_L drawn from a hot-water store is given. It is shown that different definitions may differ up to several percent.
- A formula is given which makes possible the calculation of P_L from easily measurable quantities.
- The measurement of those quantities and the associated errors are discussed.
- Some important recommendations for testing solar domestic hot-water (SDHW) systems result:
  - The pressure conditions in the store during the measurements shall comply with the manufacturer's instructions.
  - The thermal time constant of the temperature sensors can lead to large errors and shall be taken into account.
  - The volume flow-meter should be placed at the hot-water outlet.

The problems that arise in defining this power result from the temporal shift between the entry of cold water into the store, the heating of this water and the exit of hot-water. In detail, the following questions need to be answered:

- volume and mass flow rates at inlet and outlet are different, due to the thermal expansion of water and water pressure changes. Which flow rate is relevant?

— the cold-water temperature does not remain constant, the notion of *exergy of the store* is difficult to apply, and the question rises, *at what time* the cold-water temperature T_{in} entering an equation for instantaneous system power should be measured. Which consequences result?

When considering an ideal demand heater without losses, capacity and volume, these questions do not arise. Therefore, such an ideal demand heater is used as a simple reference case in D.2.1 to D.2.4.

D.2.1 Definition of the load energy Q_L

A drawoff in the interval $I = [t_0, t_1]$ is considered. At the inlet there is a mass flow rate $\dot{m}_{in}$ (t), the inlet temperature is $T_{in}(t)$ and the water density is $\rho(T_{in})$. At the outlet, there are the analogous quantities $\dot{m}_{out}$, T_{out} and $\rho(T_{out})$.

The power P_D(t) delivered by an ideal demand heater is the product of a mass flow rate times the energy necessary to heat one mass unit from inlet temperature T_{in} to outlet temperature T_{out}:

$$P_D(t) = \dot{m}(t)\left[h\left(T_{out}(t)\right) - h\left(T_{in}(t)\right)\right] \quad \text{(D.1)}$$

Here the mass flow rate through the demand-heater is called $\dot{m}$, and h denotes the mass specific enthalpy of water. In this demand-heater case, $\dot{m}_{in} = \dot{m}_{out}$ holds.

Equation (D.1) is equivalent to

$$P_D(t) = \dot{m}(t)\bar{c}_p\left(T_{in}, T_{out}\right)\cdot\left(T_{out} - T_{in}\right) \quad \text{(D.2)}$$

where $\bar{c}_p\left(T_{in}, T_{out}\right)$ denotes the specific heat of water averaged over the temperature interval $\left[T_{in}, T_{out}\right]$.

The power P_L or energy Q_L delivered by a hot-water store shall be calculated in a similar manner. But the water entering the store remains there for a while, it is then heated (in general) and it is drawn off later. Therefore, what is meant by $\dot{m}$, T_{in} and T_{out} shall be defined more clearly.

$\dot{m}_{in}$ and $\dot{m}_{out}$ are in general *not* equal (nor are $\dot{V}_{in}$ and $\dot{V}_{out}$); on the contrary, these quantities may differ up to several percent due to thermal expansion of store and water, as well as due to water pressure changes.

The user has water of temperature T_{in} at their disposal and consumes water of temperature T_{out} with a mass flow rate $\dot{m}_{out}$. The energy dQ delivered by the store in the time interval dt is now defined as the energy an ideal demand heater would need to heat water with mass d m_{out} from T_{in} to T_{out}:

$$\mathrm{d}Q = \bar{c}_p\left(T_{in}, T_{out}\right)\cdot\left(T_{out} - T_{in}\right)\cdot \mathrm{d}\, m_{out} \quad \text{(D.3)}$$

This is consistent with the observation that the user is mainly interested in the amount and temperature of water that flows from the tap. The minimum amount of energy needed and the amount of water fed into the store is a consequence of the user's hot-water demand and the current cold-water temperature.

The amount of heat Q_L drawn off in an interval I results as

$$Q_L = \int_I \dot{m}_{out}\, \bar{c}_p\left(T_{in}, T_{out}\right)\cdot\left(T_{out} - T_{in}\right)\mathrm{d}t \quad \text{(D.4)}$$

The problem is now: measure $\dot{m}_{out}$, T_{in} and T_{out} with sufficient accuracy and time resolution to calculate Q_L with a certain maximum error ΔQ_L.

Here it is assumed that Q_L should be evaluated with an error of less than 2 %.

D.2.2 Measurement of the mass flow rate $\dot{m}_{out}$

In general, mass flow is not measured directly. Therefore, the real mass flow shall be calculated.

If the volume flow-meter is capable of withstanding the temperatures and temperature changes at the outlet, and if its accuracy is not deteriorated by these temperature changes, it should be mounted at the hot-water outlet as close as possible to the store, but after the temperature sensor.

In this case, Q_L shall be calculated according to

$$Q_L = \int_I \rho(T_{out})\dot{V}_{out}\overline{c}_p(T_{in}, T_{out}) \cdot (T_{out} - T_{in})\,\mathrm{d}t \tag{D.5}$$

However, if the volume flow-meter must be mounted at the cold-water inlet, $\dot{m}_{out}$ needs to be calculated from $\dot{V}_{in}$ and the store has to be considered in more detail. The store shall have the volume V_S, which depends on the temperature distribution inside the tank. V_S is assumed to change by $\mathrm{d}V_S$ during the time interval d*t* due to thermal expansion of the store material. Then the following holds:

$$\mathrm{d}V_{in} = \mathrm{d}V_{out} \tag{D.6}$$

It is assumed that V_S depends approximately linearly on the mean temperature inside the store,

$$V_S \approx \left(1 + 3\alpha\overline{\theta_S}\right)V_S^0 \tag{D.7}$$

where α denotes the linear expansion coefficient of the store material. The change of store volume d*V*s is given by

$$\mathrm{d}V_S = 3\alpha d\overline{\theta_S}V_S^0 \approx 3\alpha(T_{out} - T_{in})\mathrm{d}V_{in} \tag{D.8}$$

Now the mass $\mathrm{d}m_{out}$ drawn from the store is given by:

$$\mathrm{d}m_{out} = \rho(T_{out})\mathrm{d}V_{in}\left(1 - 3\alpha(T_{out} - T_{in})\right) \tag{D.9}$$

The energy Q_L drawn from the store can now be calculated from the measured quantities $\dot{V}_{in}$, T_{in} and T_{out}:

$$Q_L = \int_I \underbrace{\underbrace{\rho(T_{out})\dot{V}_{in}\left(1 - 3\alpha(T_{out} - T_{in})\right)}_{\dot{m}_{out}}\overline{c}_p(T_{in}, T_{out})}_{\dot{C}_L} \cdot (T_{out} - T_{in})\,\mathrm{d}t \tag{D.10}$$

Here, $\dot{C}_L$ denotes the thermal capacitance rate that is used as an input variable in the method described in Annex A.

Values of the density of water and the expansion coefficient of the store material at $T_{out} = 60$ °C and $T_{in} = 10$ °C show that the volume of a stainless steel tank[4)] changes by approx. 0,3 % and the density of water changes by 1,7 %. Therefore, the volume change of the store can be neglected, but the density change is significant and the draw-off mass should be evaluated as outlined above.

4) $\alpha = 2 \times 10^{-5}$ K^{-1}.

Therefore, Equation D.10 can be simplified to

$$Q_\mathrm{L} = \int_I \underbrace{\underbrace{\rho\left(T_\mathrm{out}\right)\dot{V}_\mathrm{in}}_{\dot{m}_\mathrm{out}} \overline{c}_p\left(T_\mathrm{in}, T_\mathrm{out}\right)}_{\dot{C}_\mathrm{L}} \cdot \left(T_\mathrm{out} - T_\mathrm{in}\right)\mathrm{d}t \qquad \text{(D.11)}$$

In Equation D.11, it is assumed that the pressure of the cold-water inlet is kept constant during the test, and that there are no one-way valves at the inlet and no expansion vessels. This means that during the heating of the store, the expanding water will push cold water from the bottom of the store back into the cold-water-inlet pipe if the store is under pressure, or hot-water drips from the tap in the case of a no-pressure-store. Both fluid flows should be ignored, since they are not associated with a useful draw-off.

If the pressure of the cold-water inlet cannot be kept constant, a one-way valve should be mounted at the store inlet. In this case, a means of relieving the pressure increase during the heating of the store shall be provided (e.g. a pressure-relief valve). If a pressure-relief valve is used, it should be mounted in such a manner that it drains cold water from the bottom of the store, at best from the cold-water pipe between the one-way valve and the store inlet. Then, Equation D.11 should also be used.

However, if an expansion vessel is mounted, the assumption of equal volume flow rates at the inlet and the outlet no longer holds. Then, fluid mass is conserved across the store, and the calculation of the mass flow rate at the outlet from volume flow rate measurements at the inlet is made difficult, since the expansion vessel will empty a part of its content into the store at the beginning of the draw-off. In this case, the mass flow rates should be assumed to be equal at inlet and outlet, yielding the equation

$$Q_\mathrm{L} = \int_I \rho\left(T_\mathrm{in}\right)\dot{V}_\mathrm{in}\overline{c}_p\left(T_\mathrm{in}, T_\mathrm{out}\right)\left(T_\mathrm{out} - T_\mathrm{in}\right)\mathrm{d}t \qquad \text{(D.12)}$$

because then the fluid mass conservation condition is observed and the error is minimized, at least for the case of constant draw-off temperature.

Another effect that can influence operation of an SDHW system when it is operated in no-pressure mode is: the (pressure-dependent) formation of bubbles on the surface of an immersed heat exchanger, especially between the fins. SDHW systems shall be tested with the pressure conditions recommended by the manufacturer; a non-pressurized test of a normally pressurized system can lead to an underestimation of the solar fraction by several percent.

The temporal behaviour of the inlet temperature should also be considered. Ideally, the inlet temperature should be constant. Large changes during the test would mean testing under unrealistic conditions. Moreover, energy could be gained from this temperature change, and the notion of store exergy would not be applicable. Therefore, the inlet temperature should remain as constant as possible during each system test sequence. To satisfy this requirement, the inlet pipe should be rinsed through a by-pass waste valve for a few minutes before each draw-off.

D.2.3 Measuring the inlet and outlet temperature

Here several error sources can be distinguished and must be considered:

a) Common mode errors of T_in and T_out at constant temperatures.

b) Errors of ($T_\mathrm{out} - T_\mathrm{in}$) at constant temperatures.

c) Errors of changing temperatures due to thermal inertia of sensors and the flow time of water in the pipes.

Ad a): Common mode errors enter the density and heat capacity. A consideration of the listed values of these quantities shows that even a common mode error of 10 K yields only an error of 1 % in Q_L. However, for the black-box SDHW system model, the store losses and the collector losses are calculated using the temperature difference between the ambiance and the bottom of the store and a common mode error of the water temperatures causes an error in the calculation of these losses. Therefore, a common mode error of 0,3 K can be tolerated.

Ad b): Q_L is approximately linear in (T_{out} – T_{in}); therefore the error in temperature measurements should be no greater than 0,1 K.

Ad c): The error sources considered up to now are errors of the power P_L and do not depend on the temporal behaviour of P_L. On the other hand, the errors due to thermal inertia appear only when P_L is changing, and they do *not* average out but lead to an underestimation of Q_L, in general.

Let us assume that, at time t_0, both sensors are at the same temperature (e.g. store ambient temperature), that the store is fully mixed and now a drawoff with constant mass flow rate $\dot{m}_{out}$ begins and lasts until t_1, when the draw-off ends. If the sensors have a time constant τ, then the resulting error in Q_L is:

$$\frac{\Delta Q_L}{Q_L} \approx -\frac{\tau}{t_1 - t_0} \qquad \text{(D.13)}$$

The following recommendations for system testing result (for requirements, see the main text of this part of ISO 9459).

— The sensors should have a very short response time. This can be reached using thermocouples or small RTDs.

— The sensors should be mounted close to the tank to avoid long delays and dead volumes in the pipes. The piping from sensor to store should be insulated very well to obtain thermal contact between sensors and store content.

— If possible, each draw-off should be started with 60 s of drawoff with reduced flow rate, to reduce the power at those times when the error of the temperatures is large.

— Unnecessarily short drawoffs should be avoided

D.2.4 Numerical calculation of Q_L and $\dot{C}_L$

Because of the fast variation of T_{out} during drawoff Q_L and $\dot{C}_L$ should be calculated by the data acquisition system using the instantaneous values of temperatures and flow rate. It is necessary to be able to calculate $\rho\left(T_{out}\right)$ and $\bar{c}_p\left(T_{in}, T_{out}\right)$ easily from T_{in} and T_{out}. To calculate these quantities, quadratic polynomials are sufficient to reach an accuracy of 10^{-3} in the range between 0 °C and 100 °C. The following formulas have been obtained through linear regression from values listed in the *Handbook of Chemistry and Physics*, 60th Edition, CRC Press, Boca Raton, Florida, USA:

$$\rho(\theta) = \left(1\,000{,}67 - 7{,}3845 \times 10^{-2}\ °\text{C}^{-1}\theta - 3{,}547 \times 10^{-3}\ °\text{C}^{-2}\theta^2\right)\frac{\text{kg}}{\text{m}^3} + \Delta\rho$$

$$\left|\Delta\rho\right| < 0{,}8\frac{\text{kg}}{\text{m}^3} \qquad \left|\Delta\rho\right| < 0{,}5\frac{\text{kg}}{\text{m}^3}\ \text{for}\ \theta > 3\ °\text{C} \qquad \text{(D.14)}$$

$$\bar{c}_p\left(\theta_1, \theta_2\right) = \left(4{,}20028 - 5{,}048 \times 10^{-4}\ °\text{C}^{-1}\left(\theta_1 + \theta_2\right) + 4{,}097 \times 10^{-6}\ °\text{C}^{-2}\left(\left(\theta_1 + \theta_2\right)^2 - \theta_1\theta_2\right)\right)\frac{\text{kJ}}{\text{kgK}} \qquad \text{(D.15)}$$

NOTE The right side of Equation D.15 has been cast into a form yielding a minimum number of multiplications.

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ICS 27.160; 97.100.99

Price based on 35 pages