ISO 9459-5

System Performance Characterization by Means of Whole System Tests and Computer Simulation

27.04.1997

Contents

Foreword

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

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies.

International Standard ISO 9459-5 was prepared by Technical Committee ISO/TC 180 Solar Energy.

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
- 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

Annexes A, B and C form an integral part of this part of ISO 9459. Annex D and E are for information only.

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, *Part 1: Solar heating -- Domestic water heating systems: Performance rating procedure using indoor test methods,* involves testing for periods of one 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 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 applies to solar plus supplementary systems. The performance test is a 'black box' procedure which produces coefficients in a correlation equation that can 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 is limited to predicting annual performance for one load pattern.

Testing and computer simulation

ISO 9459-4, 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.

ISO 9459-5 presents a procedure for dynamic testing of complete systems to determine system parameters for use in a computer model. 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 permit 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 reliability and safety

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 is needed to predict the yearly system gain sufficiently accurate 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 stationarity requirements in the tests, and, due to the 'black box' approach, no measurements inside the store or inside the collector loop are required.

1 Scope

This part of International Standard ISO 9459 specifies a method for outdoor laboratory[1] testing of solar domestic hot water (SDHW) systems. 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.

1.1 System Types

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 the validation requirements described in Annex B are satisfied.

1.2 System Dimensions[2]

a) The collector aperture area of the SDHW system shall be between 1 and 10 m^2.

b) The storage capacity of the SDHW system shall be between 50 and 1000 liters.

c) The specific storage tank volume shall be between 10 and 200 liters per square meter of collector aperture area.

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 according to Clause 6.

b) External auxiliary heaters shall be disabled during the test. They are *not* considered to be part of the system being tested, see Clause 5.1.6.2.

Note 1 An integrated auxiliary heater is an electrical heater or heat exchanger driven by non-solar energy source located in the storage tank of the solar heating system. An external auxiliary heating is located outside of the storage tank of the solar heating system. There is no feed-back from an external auxiliary heater on the operation of the solar heating system. Therefore an external auxiliary heater is not considered part of the solar heating system.

Note 2 This standard can be applied to systems that have an integrated auxiliary heating in the form of an immersed gas heater, provided

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

b) 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;

c) During performance predictions the auxiliary heat demand is converted to a gas consumption.

---

1) 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.

2) 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 effect details of the procedure, hence application to systems outside of the specified range requires validation tests (see annex B).

1.4 Limits

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

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

c) 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 part of the system being tested.

d) The test procedure cannot be applied to SDHW systems with concentrating collectors or systems with collectors with incidence angle characteristics that differ significantly from glazed flat plate collectors[3).

e) The test procedure cannot be applied to SDHW systems with overheating protection devices that significantly influences the system behaviour under normal operation[4]

---

3) Systems with non-flat plate type incidence 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.

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

2 Normative References

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; Performance Rating Procedure Using Indoor Test Methods*
ISO 9459-2	*Solar Heating - Domestic Water Heating Systems; Performance Testing for Solar Only Systems*
ISO 9459-3	*Solar Heating - Domestic Water Heating Systems; Performance Testing for Solar Plus Supplementary Systems*
ISO 9488	*Solar Energy - Thermal Applications - Vocabulary*
ISO 9846	*Solar Energy - Calibration of a Pyranometer Using a Pyrheliometer*

3 Definitions

For the purposes of this part of ISO 9459, the following definitions apply. See also definitions in ISO/FDIS 9488.

3.1
capacitance rate
the product of 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

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/FDIS 9488)

3.4
components
parts of the solar hot water system including e.g. collectors, store, pumps, heat exchanger, controls

3.5
conditioning
at the beginning and at the end of each test sequence a separate conditioning of the store is carried out in compliance the conditions specified in Clause 6.2.2.1.4.

Note 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

3.6
differential temperature controller
a device that is able to detect a small temperature difference, and, to control pumps and other electrical devices according to this temperature difference

3.7
draw-off temperature
the temperature of hot water withdrawn from the system

3.8
dynamic system testing
a procedure is called dynamic, if it takes into account time varying processes in performance prediction as well as in parameter identification

3.9
external auxiliary heating
auxiliary heating element (heat exchanger driven by a non-solar energy source or built-in electrical heater) located outside of the storage tank. There is no feed-back from the auxiliary heater on the operation of the solar heating system. Therefore an external auxiliary heating is not considered part of the solar heating system

3.10
fluid transport
the transfer of air, water, or another fluid between components

3.11
integrated auxiliary heating
auxiliary heating element (electrical heater or heat exchanger driven by non-solar energy source) located in the storage tank

3.12
load side heat exchanger
a device to transfer the heat from a solar store containing non-potble water to potable mains water drawn off

3.13
measurement time
total elapsed time for a particular test sequence

3.14
non-stationary conditions
meteorological and system operation conditions varying in time

3.15
output variable
time and system state dependent quantity in a system under operation conditions, accessible to measurement (e.g. store draw-off power)

3.16
parameter
a quantity characterizing a system without being dependent on operating conditions. Parameters are determined by an evaluation program using measured data

3.17
preheating
see solar preheat system (8.4 in ISO/FDIS 9488)

3.18
storage capacity
the amount of sensible heat that can be stored per Kelvin of temperature increase

3.19
storage tank, store
(thermal) storage device (see ISO 9459-1)

3.20
surrounding air velocity
the velocity of the ambient air passing over the collector at a distance of 150 mm above its aperture plane

3.21
test sequence
continuous measurement set with a compulsory conditioning at the beginning and a recommended conditioning at the end

4 Symbols, Units, 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}]	Thermal heat capacity of the store (**P**)
D_L	[-]	Draw-off mixing parameter (**P**)
$\dot{C}_S$	[WK^{-1}]	Load side capacitance rate through the store
f_{aux}	[-]	Fraction of auxiliary heated part of the store (**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
P_{cp}	[W]	Collector pump power
P_L	[W]	Load power, $P_L = \dot{C}_S(T_S - T_{cw})$
P_{net}	[W]	Net system power, $P_{net} = P_L - P_{aux}$
Q_L	[MJ]	Load energy
$\mathrm{Q}_{\mathrm{aux}}$	[MJ]	Energy from auxiliary heating
$\mathrm{Q}_{\mathrm{net}}$	[W]	Net system gain $Q_{net} = \int P_{net}\mathrm{d}t = \int\left(\dot{C}_L(T_L - T_{cw}) - P_{aux}\right)\mathrm{d}t$
R_L	[K/W]	Thermal resistance of load side heat exchanger (**P**)

S_C	[-]	Solar loop stratification parameter (**P**)
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
$T_S^{\min}$	[°C]	Minimum outlet temperature of the store
T_{sa}	[°C]	Ambient air temperature in vicinity of the store
u_C	[$Wm^{-2}K^{-1}$]	Specific loss coefficient of the collector loop
u_C^*	[$Wm^{-2}K^{-1}$]	$u_C^* = u_C/(\alpha\tau)$ (**P**)
U_S	[WK^{-1}]	Loss coefficient of the store (**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
$(\alpha\tau)$	[-]	Effective transmittance-absorbtance product
ΔT_{off}	[K]	Temperature difference for disabling the collector loop
ΔT_{on}	[K]	Temperature difference for activating the collector loop
β	[rad]	Collector tilt angle
γ	[rad]	Collector azimuth angle
$\rho_w(T_S)$	[kg/l]	Densitiy of water at temperature T_S
θ	[rad]	Angle of incidence
τ_F	[s]	Filter time constant

5 Apparatus

This Clause deals with the requirements for mounting and location of the system being tested and gives a description of the test facility.

The general aspects of installation, operation and measuring of the system outlined here shall be followed in order to assure the comparability of test results.

5.1 Mounting and Location of the SDHW System

In this Clause[5)] requirements are summarized concerning system installation and the local environment surrounding both the storage tank and the collectors.

5.1.1 Safety

The system shall be mounted in a manner ensuring safety to personnel. Due consideration shall be given to the likelihood of glass failure and the leakage of hot liquids. Mounting shall be able to withstand the effects of wind gusts.

5.1.2 System Mounting

The complete system shall be mounted according to 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. The system mounting shall in no way obstruct the aperture of collectors and the mounting structure shall not significantly affect the back or side insulation of the collectors or the storage tank.

5.1.3 Collectors

5.1.3.1 Collector Location

Collectors designed for integration onto a roof may have their backs protected from the wind, although this shall be reported with the test results. In that case, the heat loss coefficient of the collector test-rig shall be set according to the manufacturer's guidelines or shall have a value of $0.35 \pm 0.05\ \mathrm{Wm^{-2}K^{-1}}$ 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.

5.1.3.2 Collector Azimuth Orientation

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

5.1.3.3 Collector Tilt Angle

The system shall be tested at a collector tilt angle within ± 5° of the geographical latitude of the test site. If this is not possible or if the system is designed for a special collector tilt angle, the tilt angle recommended by the manufacturer shall be used. This shall be reported with the test results. The tilt angle shall remain constant throughout the test.

5.1.3.4 Shading of Collectors from Direct Solar Irradiance

The collector shall be positioned in such a manner that shadows of any object other than the collector itself will not be cast into the collector aperture at any time during the test period.

---

5) This Clause is consistent with parts 2 and 3 of standard 9459 in order to assure transparency of test results.

5.1.3.5 Diffuse and Reflected Solar Irradiance on Collector Plane

The collector shall be located where there will be no significant 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 on to both the back and the front of the collector shall be minimised. 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. Surfaces to be avoided in the collector's field of view include large expanses of glass, metal or water.

5.1.3.6 Heat Transfer Fluid

The heat transfer fluid used in the system during testing shall be the fluid recommended by the manufacturer. If there is no recommendation, either water or a mixture of 30 % volume ethylene glycol or propylene glycol and water shall be used. The fluid used shall be reported. For all systems the fluid flow rate as resulting from system operation as recommended by the manufacturer shall be used.

5.1.3.7 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, or to another value selected by the test engineer. ΔT_{off}, if adjustable, should be set to 2 K. The controller setting shall be stated clearly in the test report. If only manual control is given without manufacturer's recommendations, the pump shall be activated not later than two hours after sunrise and shall be turned off not earlier than two hours before sunset each day; the pump shall be turned off between sunset and sunrise.

5.1.4 Storage

5.1.4.1 Storage Tank Location

The store shall be installed in a position allowed in the manufacturer's installation instructions.

5.1.4.2 Storage Ambient Conditions

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

Storage tanks separated from the collector array should be situated in a closed room taking into account the requirements regarding pipe length as stated in 5.1.5 and manufacturer's prescriptions. The ambient temperature of the store shall be according to 6.2.2.1.3.

5.1.5 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 ± 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 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. All pipes and pipe connections shall be properly insulated so that thermal losses are minimized.

5.1.6 Hiliary Heating

5.1.6.1 Integrated Auxiliary Heating

Integrated auxiliary heating can be provided either by a heat exchanger or an immersed electrical heater.

5.1.6.1.1 Heat Exchanger

If a heat exchanger driven by a non-electrical heat source is used, an electrical demand 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 100 ± 30 W per liter of store volume above the lowest part of the heat exchanger.

5.1.6.1.2 Immersed Electrical Heater

If an immersed electrical heater is used, the heater delivered with the system shall be used. If no such heater is delivered with the system, an electrical heater with a nominal power of 25 ± 8 W per liter of store volume above the lowest part of the heater shall be used.

5.1.6.2 External Auxiliary Heating

External auxiliary heating shall be disabled. Systems with external auxiliary heating shall be tested as systems without external 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.

5.1.6.3 Insulation

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. If auxiliary heating is 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, in order to avoid reverse thermosiphonic convection.

5.1.7 Mixing Valve

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

5.1.8 Protection from Long-Wavelength Radiation and Thermal Convection

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 which 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.

5.2 Test Facility

This Clause describes the test facility, the instrumentation and the location of the sensors.

5.2.1 Scheme of the Test Facility

A typical installation for measurement of the variables listed in Table 6.5 is shown in Figure 5.1. A system with forced circulation flow in the collector loop and with an indoor store equipped with electrical auxiliary heating is shown. For different system designs, e.g. thermosiphon systems or store located outside the building, the installation varies accordingly. However, the measurement points remain the same.

The collectors and the storage tank shall be mounted according to the prescriptions in 5.1.

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 6.2.2.1.1.

Note 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 rinse this part of the piping immediately before each draw-off in order to provide constant mains water temperature.

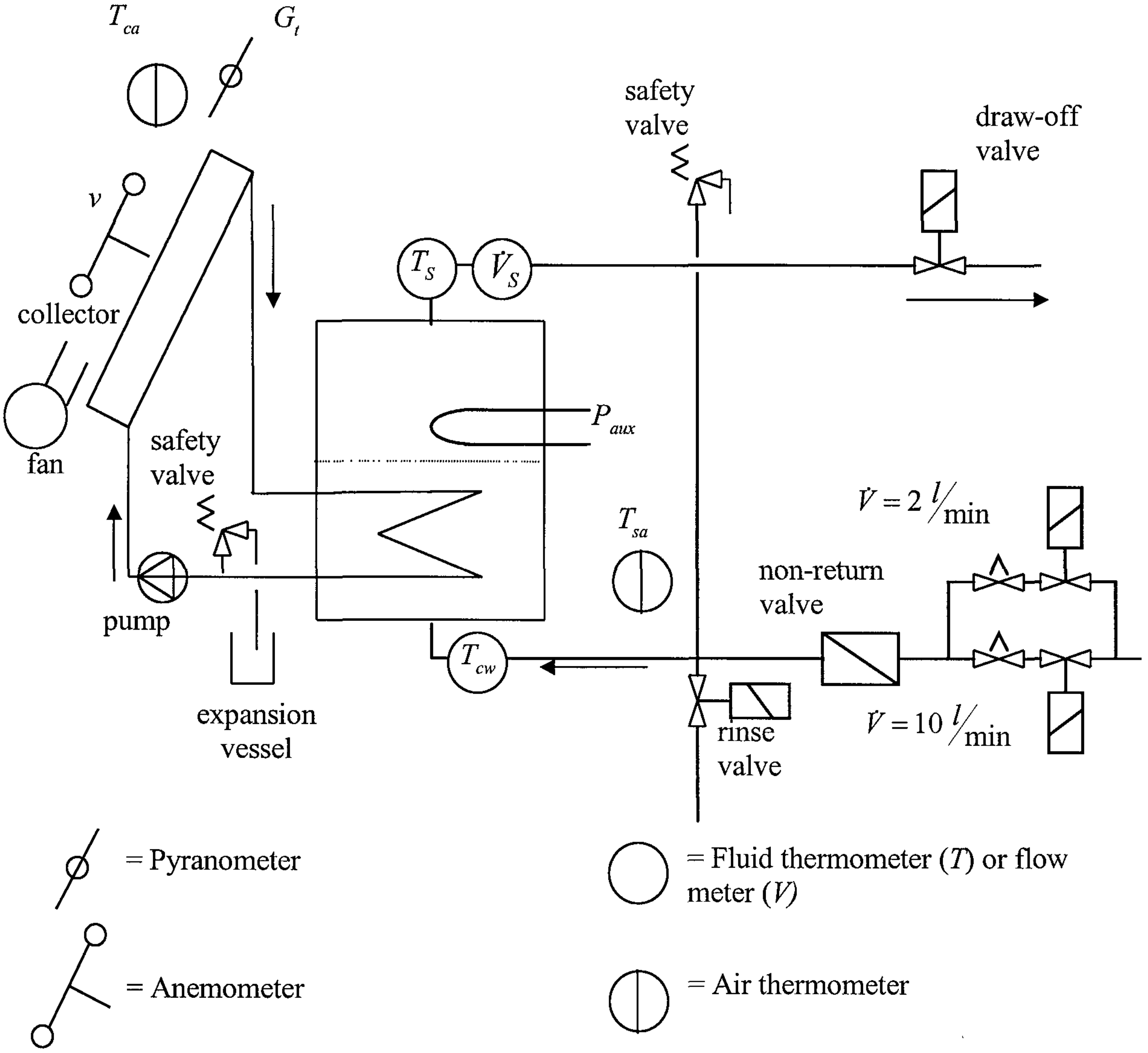


Figure 5.1 - Typical test facility for a system with forced circulation of fluid in the collector loop and storage tank equipped with an immersed electrical auxiliary heater. See 5.2.3.5 for alternative location of the flow meter

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 loss coefficient does not exceed 0.15 W/K for each pipe.

Note If the flow in the pipe is not turbulent, mixing devices are required immediately upstream of temperature sensors.

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 fulfill all requirements specified in Clause 6.

5.2.2 Instrumentation

This Clause deals with the accuracy required for the measuring devices. The maximum errors relate to the corresponding measured value including data-logger accuracy.

5.2.2.1 Solar Radiation Measurement (Radiometers)

A pyranometer shall be used to measure the solar radiation. The pyranometer shall have characteristics according to class I of WMO classification **and** ISO 9060.

The pyranometer shall be calibrated using a standard pyrheliometer according to ISO 9060 and ISO 9846. Any change of the responsivity of more than ± 1 % over a year's period shall warrant the use of more frequent calibration or replacement of the instrument if the instability is permanent. If an instrument is damaged in any significant manner, it shall be recalibrated to check the stability of the calibration factor and time constant. In case of a replacement of one of the domes the cosine response shall also be checked.

5.2.2.2 Temperature Measurement

The accuracy and repeatability of the instruments including their associated readout devices shall be within the limits given in Table 5.2. The time constant shall be less than 3 s for sensors measuring fluid temperatures.

Parameter	Instrument Accuracy	Instrument Repeatability
Temperature, Ambient air	± 0.5 K	± 0.2 K
Temperature, cold water inlet	± 0.3 K	± 0.1 K
Temperature difference across system (cold water in to hot water out)	± 0.1 K or 1 % whichever higher	± 0.1 K

Table 5.2: Temperature Measurement Accuracy and Repeatability

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.

5.2.2.3 Volumetric draw-off rate measurements

The accuracy of the volumetric draw-off rate measurement shall be equal to or better than ±1.0 % of the measured value in volume units per draw-off as defined in 6.2.2.

5.2.2.4 Electric Energy

The electrical energy used shall be measured with an accuracy of ±1.0 % of the reading or ±15 Wh, whichever is greater.

5.2.2.5 Elapsed Time

Elapsed time measurements shall be made to an accuracy of ± 0.2 %.

5.2.2.6 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 ms^{-1}. To meet this requirement, the start velocity of the instrument shall be 0.5 ms^{-1} or less.

5.2.3 Location of Sensors

5.2.3.1 Pyranometer

The pyranometer shall be mounted and operated according to 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.

5.2.3.2 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.

5.2.3.3 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 tank and system components and not further away than 10 m from the system.

5.2.3.4 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[6]. 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.

5.2.3.5 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 Fig. 5.1. If variations of the draw-off temperature deteriorate the flow-meter accuracy such that it does not comply with the requirements of 5.2.2.3, it shall be installed in the mains water pipe directly adjacent to the measurement point of the mains water temperature[7]. Depending on the location of the volumetric flow-meter and the system setup, the capacitance rate and the load shall be computed according to the formulas given in 6.2.3.2.

5.2.3.6 Anemometer

The surrounding air velocity shall be measured on a surface (minimum dimensions 1 m × 1 m) fixed in the same plane as the collector surface. The anemometer shall be positioned at a height approximately equal to the height of

---

6) It is recommended that the hot water sensor is mounted so close to the store that they are thermally coupled to the store even when there is no draw-off.

7) As explained in Annex D, the mass flow rates at the store inlet and outlet differ up to 2 % due to the thermal expansion of water. 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 6.2.3.2 and discussed in Annex D.

the centre of the collector array. The height of vanes should be 150 mm above the surface to which the anemometer is mounted. The anemometer should be situated as close as possible to the collector array, the distance shall not exceed 1 m. If the fans are used, the anemometer shall be placed so that it measures the velocity of the air stream passing over the collector.

5.2.3.7 Additional Sensors

It is allowed to add additional sensors in the system in order to obtain data for characterisation of components in parallel with the test sequences in this standard, provided the normal functioning of the system is not influenced.

6 Test Method

This Clause describes the measurement procedure and the processing of the measured data.

6.1 Principle

The theoretical model described in [1] is used to characterize SDHW system performance under non-stationary operation. A description of the theoretical background of the test method is given in Annex A.3. 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 as described in 6.2.2 to ensure accurate determination of the system parameters. Measured data shall be pre-processed as described in 6.2.3 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. 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.

6.2 Test Procedure

6.2.1 General Preparation

The collector circuit and the store shall be filled with a fluid according to 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 collector glazing and the pyranometer shall be kept clean during performance monitoring.

6.2.2 Test Sequences

A test consists of several test sequences, called $\boldsymbol{S}_{sol}$, $\boldsymbol{S}_{store}$, and $\boldsymbol{S}_{aux}$:

$\boldsymbol{S}_{sol}$: A test sequence containing a number of consecutive days of measurement with continuous system operation. It shall be carried out according to a test sequence time schedule based on two specific daily operation conditions named **Test A** and **Test B** as described in this Clause. The daily tests take into account system specific dimensions, i.e. store volume and collector array area and/or actual draw-off temperature.

$\boldsymbol{S}_{store}$: Store loss test sequence.

$\boldsymbol{S}_{aux}$: A test of the operation of the system with integrated auxiliary heater under low solar irradiation conditions.

Informative Note on the Draw-off Profile: 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, does each parameter of the model get a chance to show its influence on the behaviour 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 minimum time. Here, system state means a combination of 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 a '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 all relevant system states are covered, i.e. testing times can be much longer to achieve the same performance prediction accuracy.

This standard 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 collector aperture area and store volume may vary up to a factor of 20 for the systems considered in this standard. 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 collector inlet temperature) must be kept cold for some interval 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.

6.2.2.1 General

6.2.2.1.1 Mains Water Temperature

During draw-offs[8], 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/hour.

6.2.2.1.2 Air velocity Surrounding the Collectors

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

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

Shall **not** be used for systems with unglazed collectors.

W_{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 Wm^{-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.

Shall not be used for systems with unglazed collectors.

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

Mandatory for systems with unglazed collectors.

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

(1) exceeding 3 m/s for at least two days under Test B conditions (between 6:00 and 18:00) during sequence Ssol, and

(2) be below 1.5 m/s with the same requirements as in (1).

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

---

[8] 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.

6.2.2.1.3 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 and shall not differ on average from mains water temperature by more than ± 10 K. The location of the store shall be described in the test report.

6.2.2.1.4 Control of the Auxiliary Heating

Control of the integrated auxiliary heating shall be activated or disabled as prescribed in 6.2.2. The set temperature shall be 55 ± 5 °C if not otherwise specified by the manufacturer. For sequences where the maximum temperatures specified in Clause 6.2.2.3 are applied the set temperature shall be equal to the maximum temperature minus 5 K.

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

6.2.2.1.5 Conditioning

At the beginning and at the end of each test sequence the store is brought to uniform temperature by applying a draw-off rate[9] of 10 ± 1 l min^{-1}. 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 2 K.

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

6.2.2.2 Days of type Test A

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 6.1. 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.

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

Table 6.1 - Draw-off start times for test A

Note 1 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.

Note 2 For test facilities intending to test several systems simultaneously with only one mains water pipe (where draw-offs must 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 6.1.

The draw-off volume flow rate9) 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 according to 6.2.2.1.1.

---

9) If the system was not designed to yield 10 l/min, the maximal design flow-rate shall be used. This shall be reported.

The volume of each draw-off for **Test A** depends on the system dimensions as specified in Table 6.2. However, the volume of any draw-off shall not be less than 20 l.

System Dimensions	Draw-off Volume
100 l m^{-2} ≤ V_S / A_C ≤ 200 l m^{-2}	0.2 V_S ± 10 %
60 l m^{-2} ≤ V_S / A_C ≤ 100 l m^{-2}	0.25 V_S ± 10 %
40 l m^{-2} ≤ V_S / A_C ≤ 60 l m^{-2}	0.33 V_S ± 10 %
20 l m^{-2} ≤ V_S / A_C ≤ 40 l m^{-2}	0.5 V_S ± 10 %

Table 6.2 - Draw-off volumes for test A

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

6.2.2.2.1 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 of 1.0 V_S ± 10 % each shall be drawn, starting between 6:00 and 7:00 solar time, with intervals of 1 h ± 5 min.

6.2.2.3 Days of type Test B

The integrated auxiliary heater (if present) shall be **enabled** at or not more than one hour after the end of the last draw-off of each **Test B** day and **disabled** at or not more than one hour 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 setpoint of the auxiliary heater shall be adjusted as specified in 6.2.2.1.4.

The draw-off profile consists of five draw-offs starting at the times specified in Table 6.3. 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.

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

Table 6.3 - Draw-off start times for test B

Note 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 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 $\boldsymbol{S}_{sol}$ shall be taken according to 6.2.2.1.1.

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 $\leq V_S / A_C \leq$ 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 according to the Table 6.4:

System Dimensions	Temperature
100 l m^{-2} $\leq V_S / A_C \leq$ 200 l m^{-2}	70 ± 5 °C
60 l m^{-2} $\leq V_S / A_C \leq$ 100 l m^{-2}	60 ± 5 °C
40 l m^{-2} $\leq V_S / A_C \leq$ 60 l m^{-2}	50 ± 5 °C
20 l m^{-2} $\leq V_S / A_C \leq$ 40 l m^{-2}	40 ± 5 °C

Table 6.4: Threshold temperatures for test B days

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

For a **Test B** day to be a valid, the irradiation in the collector plane shall exceed 12 MJ m^{-2} during this day.

6.2.2.3.1 Under-dimensioned storage tank

If system dimensions are in the range 10 l/m^2 $\leq V_S / A_C \leq$ 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 no less than 5 litre, and each draw-off shall be continued as long as the draw-off temperature exceeds a threshold temperature of 40 ± 5 °C.

6.2.2.4 Sequence S_{sol}

The measurement shall be prolonged until the following requirements are fulfilled:

- At 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 subsequence (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 subsequences with **Test A** and **Test B** days, respectively. The data of all subsequences shall then be used simultaneously for parameter identification. However, each subsequence shall start with a conditioning, the skip time (see clause A.2.3.)shall be set accordingly for each subsequence and the data from each subsequence shall be contained in one continuous data file.

6.2.2.5 Store Loss Test Sequence, S_{store}

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

Conditioning according to 6.2.2.1.4.

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

Cooling period: Takes 36 to 48 hours starting from the last draw-off of the heating period. No draw-off, no or 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 must also be covered. Alternatively its measured output can be set to zero.

  Note 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 system 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 during standstill. No valve shall be included in the collector loop for this purpose only.

Final conditioning: according to 6.2.2.1.4.

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.

The integrated auxiliary heater (if present) shall be **disabled** during the whole sequence.

6.2.2.6 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 integrated auxiliary heater under low solar irradiation is assessed. After conditioning according to 6.2.2.1.4, 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 6.2.2.1.4.

6.2.3 Data Acquisition and Processing

During measurement of the system being tested, the data specified in Table 6.5 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.

6.2.3.1 Data Sampling

All measured data during a test sequence shall be sampled with time intervals not exceeding the values specified in Table 6.5.

Note If the draw-offs are controlled by the measuring program, it is recommended to start a new data record at the beginning and the end of each draw-off period (see 6.2.3.3). It is recommended to use an integrating measuring device.

Symbol	Unit	Variable	Maximum Sampling Interval	
			Draw-off	No Draw-off
T_{cw}	[°C]	Mains water temperature	2 s[10]	30 s
T_S	[°C]	Store outlet temperature	2 s[10]	30 s
$\dot{V}_S$	[l/min]	Volumetric draw-off rate	2 s[10]	30 s
P_{aux}	[W]	Auxiliary power	2 s[10]	30 s
G_t	[Wm^{-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	[ms^{-1}]	Surrounding air velocity	30 s	30 s

Table 6.5 - Maximum Sampling Intervals of the Measured Variables

6.2.3.2 Data Processing

The sampled values shall be continuously integrated and averaged as specified in 6.2.3.3. In addition to measured variables which are used directly, the algorithm requires data on draw-off capacitance rate and draw-off load power. In general, the draw-off capacitance rate and draw-off power shall be computed according to equations 6.1 and 6.2, respectively:

$$\dot{C}_S = c_w(T_{cw}, T_S)\rho_w(T_S)\dot{V}_S \tag{6.1}$$

$$P_L = \dot{C}_S(T_S - T_{cw}) \tag{6.2}$$

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 of the water pressure (see Annex D 2.2).

a) If the *volume* flow rates at inlet and outlet are approximately equal, the draw-off capacitance rate and draw-off power shall be computed according to equations 6.1 and 6.2, respectively. This holds e.g. for a store without a one-way-valve in the mains pipe and without pressure relief valves or expansion vessels, and also for a store with a one-way-valve and a pressure relief valve.

b) If the *mass* flow rates at inlet and outlet are approximately equal, or at least the integral mass flows, the draw-off capacitance rate and draw-off power shall be computed according to equations 6.3 and 6.4. This holds e.g. for a store with a one-way-valve and an expansion vessel.

$$\dot{C}_S = c_w(T_{cw}, T_S)\rho_{cw}(T_{cw})\dot{V}_S \tag{6.3}$$

$$P_L = \dot{C}_S(T_S - T_{cw}) \tag{6.4}$$

If it is not clear which case is applicable, equations 6.1 and 6.2 shall be used.

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.

If auxiliary heating is provided by a heat exchanger, P_{aux} shall be measured in the same way as P_L, in most cases according to method b) of this clause.

---

10) In case 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.

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

6.2.3.3 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 and 5 minutes elsewhere. The recorded time shall describe the time at the end of the measurement interval, which started at the end of the previous record. The data recording interval may vary during the measurement sequence. The data in any sequence or subsequence shall be continuous, whereas sequences or subsequences may be discontinuous.

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

7 Identification of System Parameters

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.

The following options (see Annex A) shall be turned ON for the identification of system parameters:

1. `WindCollector:`	Shall be used for option $\boldsymbol{W_{fit}}$ only (see 6.2.2.1.2). The collector loss coefficient u_C^* depends linearly on the wind velocity over collector plane.
2. `DrawoffMix:`	Draw off causes mixing within the store.
3. `SolarStratification:`	Solar loop operation may generate stratification.
4. `Aux:`	For systems with integrated auxiliary heater.
5. `LoadHeatExchanger:`	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.

The filter time constant τ_F should be set to 4 hours. The draw-off related filter constant C_F (in J/K) should be set to 400 times the store volume V_S in liters (which makes $C_F \approx 0.1\ C_S$)

The skip time for each data file shall be set corresponding to 6.2.2.1.4, i.e. to the time used for the conditioning at the beginning.

Parameter identification may be carried out by the institution where the test is performed but also by another institution.

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.

Zero variance of the parameters should be used to indicate

- a singular covariance matrix, which might be caused by insufficient variability of the input data, or
- fixing of one or more parameters.

Data with a singular covariance matrix shall be rejected.

Parameters shall *not* be fixed.

8 Performance prediction

The yearly performance Q_{net} of the system shall be predicted according to Annex A.2.5 and reported using the reporting format given in Annex C. If the system fails to meet the required temperature T_D for certain loads, this shall be reported together with the performance test results.

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

Annex A

(normative)

Mathematical and Physical Basis of Dynamic SDHW System Testing

A.1 Introduction

This annex addresses special issues of short-term SDHW systems testing.

Problems are the coincidence of two facts: First, the gain of a 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', say the time in which one store volume is withdrawn, is about one day or more.

It follows that several parameters have to be determined to characterize the influence of various effects on the system under test. Furthermore, the determination of each parameter may take a time of about several multiples of the system time constant. If stationarity is required, that is if the energy in the store at the beginning and the end of the sequence, for which the integral gain is determined, has to be equal, one can easily arrive at a minimum testing time of several months.

The main idea of the method described here - the dynamic method[11] - is to minimize experimental effort and to use mathematical tools, which extract as much information as possible from the test data. Furthermore, there is no stationarity requirement on the data. This is very important, because it may take more time to get stationarity than to vary input variables for determination of one parameter.

The method described here uses the data of 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 are applied to the prediction conditions.

The method used here is intended to meet the following objectives:

- Indoor, outdoor and in situ feasibility.
- Black box test, i.e. no use is made of intrusive measurements (e.g. inside the store).
- Short term test.
- Low cost.
- Prediction possible for any meteorological and load conditions.
- Applicable to a large class of systems.
- For detailed explanation of the processes see [1], [3], [4], [5], [6].

---

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

A.2 SDHW System Testing

A.2.1 The SDHW Model

The store is modelled using a plug flow model similar to the so-called `TYPE38 Algebraic Tank Model` in the simulation program TRNSYS [7]. Fig. A.1 shows the idea of the plug flow concept.

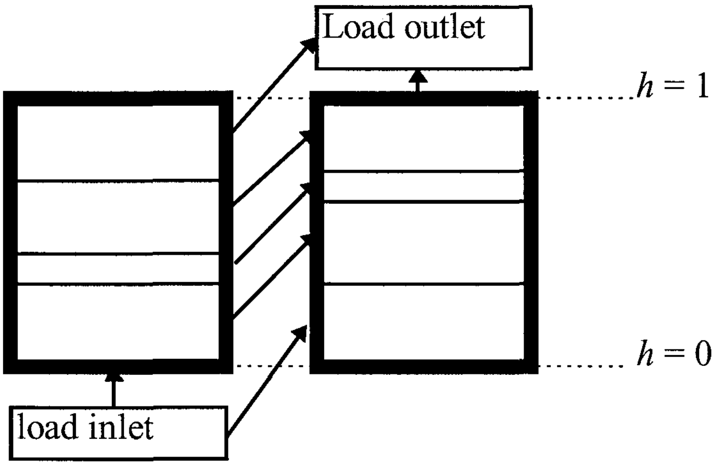
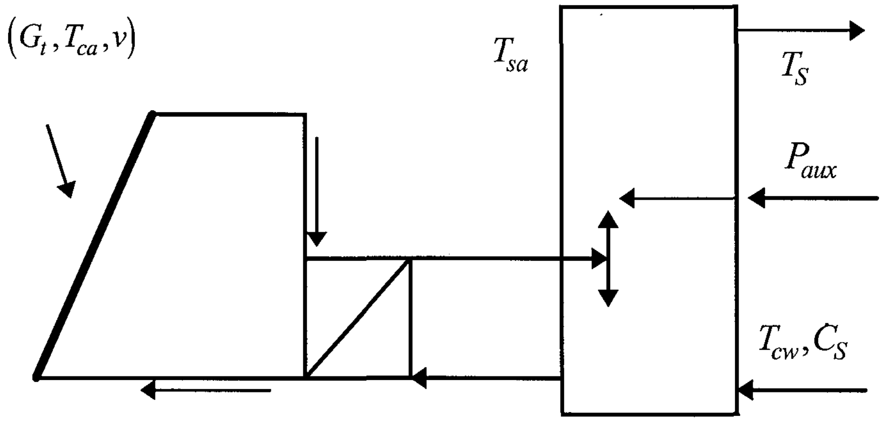


Figure A.1: Draw-off in the plug flow model

As a modification to the plug flow model, draw-off mixing is modelled. Stand-by mixing is not taken into account. The physical model is depicted in Fig. A.2. A detailed description of the model is given in [1] and A.4. The variables used here are defined in Table A.2, Table A.1 shows the list of all model parameters.



subsystem: collector loop		**subsystem: store**	
Effective collector area	A_C^*	Cold water draw-off mixing	D_L
Effective loss coeficcient	u_C^*	Overall loss coefficient	U_S
Solar loop stratification	S_C	Overall thermal capacity	C_S
		Auxiliary fraction	f_{aux}

Figure A.2: The SDHW system model. See Table A.1 for the full list of parameters

A.2.1.1 The Model Options

The following options shall be implemented:

- `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 introducing a new parameter, the thermal resistance R_L of the heat exchanger (A.4).
- **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.2.2 The Algorithm of Parameter Identification

The fit procedure used to identify the parameters is described in annex A.3. The method works by the inversion of dynamic system simulation: while simulation yields the system output from given parameters, dynamic fitting yields the parameters from the measured system gain, see Fig. A.3 and Fig. A.4.

A.2.3 Skipping Subsequences

Generally, the system state at the beginning of a sequence is not known. At any time *t* during a sequence starting at t = 0, the system state is a function of

- the initial state at t = 0, and
- the values of the input variables (irradiance, load etc.) during the interval [0,t].

At t = 0, only the initial state is important, but its influence will fade out as the system state is determined more and more by the input variables. The time when the initial state has 'faded out' enough shall be called the skip time, Δt_{skip}. Now, it is *not* the task of the fitting procedure to guess the initial state correctly - this is impossible. The fitting procedure is concerned solely with the way the system state is influenced by the input variables during the sequence.

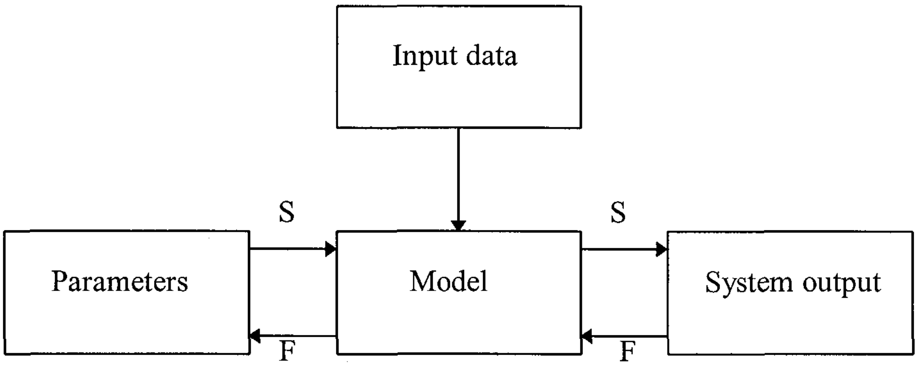


Figure A.3: Dynamic system fitting (F) can be interpreted as an inversion of dynamic system simulation (S)

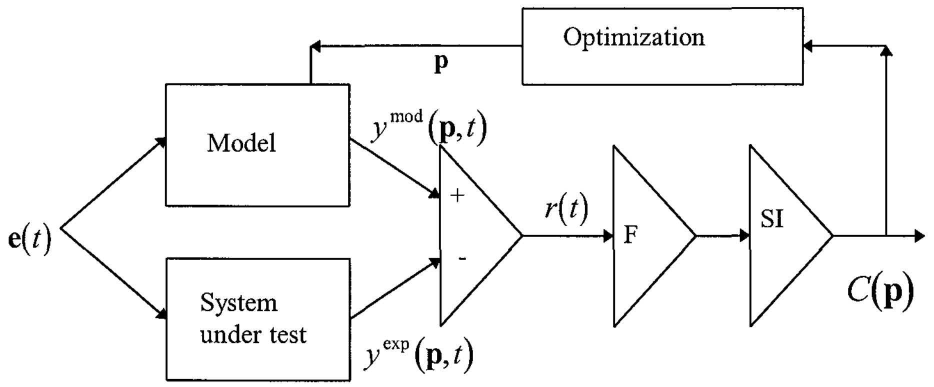


Figure A.4: The dynamic fitting procedure. During the experiment, the input e is applied to the system under test. Its measured output $y^{\exp}$ is compared to the modelled output y^{mod}, which depends on the parameters p. The integral of the square (SI) of the filtered (F) deviation *r* gives a measure $C(\mathrm{p})$ of the goodness of the fit. An optimization procedure is used to determine the value of p which yields the best fit

Symbol	Units	Range	Physical meaning
A_C^*	[m²]	≥ 0	Effective collector area.
u_C^*	[Wm^{-2}K^{-1}]	≥ 0	Effective collector loss coefficient. The collector loop power - given the store temperature T relevant for collector losses - is modelled by: $P_C = \left[G_t - u_C^*(T - T_{ca})\right]^+$.
u_v	[Jm^{-3}K^{-1}]	≥ 0	Wind speed dependence of u_C^*, Activated by model option WindCollector.
U_S	[WK^{-1}]	≥ 0	Loss coefficient of the store
C_S	[MJK^{-1}]	≥ 0.1	Thermal heat capacity of the store
f_{aux}	[-]	$\in]0,1]$	Fraction of the store volume used for auxiliary heating. Activated by model option `Aux`.
D_L	[-]	$\in [0,5]$	Mixing constant, describing mixing effects during cold water inlet (D_L = 0 for no mixing). Activated by model option DrawoffMix.
S_C	[-]	≥ 0	Stratification parameter, S_C = 0 is equivalent to a heat exchanger immersed at the bottom. Activated by model option SolarStratification.
R_L	[K/W]	≥ 0	Thermal resistance of the load side heat exchanger (systems with load side heat exchanger only). A value of R_L = 0 is equivalent to no load side heat exchanger. Activated by model option LoadHeadExchanger.

Table A.1:List of all model parameters for the SDHW model

Consequently, the model starts with an arbitrary initial state, which might be far from the initial state of the system under test. However, the difference of the system state between a correct model and the tested system will become smaller and smaller when the influence of the initial state decreases. Therefore, the fit uses the information about [0, Δt_{skip}] only for matching the correct system state at time Δt_{skip}. It does not compare modelled and measured system output during [0, Δt_{skip}], since the modelled output is adversely influenced by the difference in the initial system state.

The system shall therefore be preconditioned as described in 6.2.2.1.4. The preconditioning phase must be included in the data file of the sequence, and the skip time Δt_{skip} shall be set to the length of the preconditioning phase. Actually, the model will exactly match the purpose of a preconditioning phase: it will have a well defined system state. Note that this state can differ significantly from a uniform temperature distribution with cold water temperature.

A.2.4 The Data Files

Each data file refers to one continuous sequence of measurement.

The length of the timesteps is **not** necessarily equal between the individual data records. By contrast, it is encouraged to make use of different time steps for the sake of data compression, computation speed and accuracy. For the primary data acquisition, it is recommended to choose the length of the time steps as small as possible, and to condense the files - if useful or necessary - with a preprocessor off line for fitting. Condensing shall not significantly modify the fit result. In any case all data - except the time specification - shall represent mean values for subsequent time intervals.

symbol	unit	meaning
t	[s]	Time
T_{ca}	[°C]	Ambient air temperature in vicinity of collectors
G_t	[Wm^{-2}]	Solar irradiance in the collector plane
T_{sa}	[°C]	Ambient air temperature in vicinity of the store
T_{cw}	[°C]	Cold (mains) water temperature
T_S	[°C]	Outlet temperature of the store
$\dot{C}_S$	[WK^{-1}]	Load side capacitance rate through the store
P_L	[W]	Load power
v	[ms^{-1}]	Surrounding air velocity in collector plane
P_{aux}	[W]	Auxiliary power (if applicable)
P_{cp}	[W]	Collector pump power (if applicable)

Table A.2: Variables to be measured

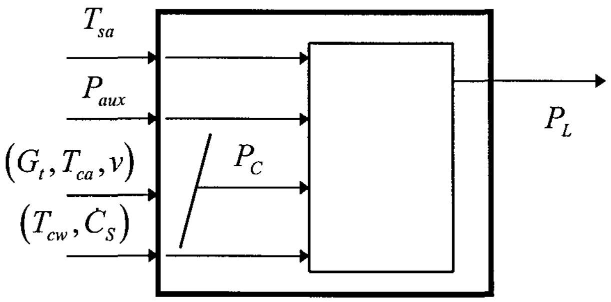


Figure A.5: System under test as Black Box

Fig. A.5 shows the definition of the input and output variables for SDHW systems. It shows that e.g. the collector power P_C is considered to be an internal variable not accessible to measurement. The variables to be measured are listed in Table A.2.

A.2.5 Long Term Performance Prediction

For long term prediction (LTP), the same model as for fitting shall be used, except for:

a) Ignoring of negative values of P_L.

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

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

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

Note: although the same model shall be used, different implementations may be used.

The ultimate use of the parameters **p** and its covariance **V** is the prediction of the yield Y(**p**, $\mathcal{D}$) for certain input data $\mathcal{D}$, i.e. the thermal energy delivered by a SDHW system for standard weather data. In the following, the algorithm to calculate Y as well as its standard deviation σ_Y is described.

A.2.5.1 The Yield Function Y(p, $\mathcal{D}$)

It seems to be straightforward to use the same model as used for testing, but now for the data $\mathcal{D}$, and to integrate the yield quantity Y of interest. However, there are two problems:

Firstly the model must be used slightly different, as described above.

Secondly, the problem of the unknown initial state arises. In testing, the beginning of the data set is skipped as described in A.2.3. For predicting, it is assumed that the data $\mathcal{D}$ are repeated cyclically. Hence the initial state is taken equal to the final state. Technically, a certain interval at the beginning is (although simulated using an arbitrary initial state) skipped, i.e the yield Y is not taken into account. Then the rest of the data is simulated and finally the skipped interval is simulated again, but now the yield Y is taken into account. This makes sure that all data $\mathcal{D}$ are taken into account, with a negligible influence of the initial state. A LTP skip time of six days shall be used.

A.2.5.2. Error of the Predicted Yield Function Value

Having defined the yield function Y(**p**, $\mathcal{D}$), its standard error is estimated. The function Y(**p**, $\mathcal{D}$) is linearized around $\hat{\mathbf{p}}$:

$$Y(\hat{\mathbf{p}}+\Delta\mathbf{p},D)\approx Y(\hat{\mathbf{p}},D)+\sum_i\frac{\partial Y(\mathbf{p},D)}{\partial p_i}\Delta p_i \qquad \text{(A.1)}$$

Then the standard error σ_Y of Y is:

$$\sigma_Y^2=E_{\mathbf{p}}\left[(Y(\mathbf{p},D)-Y(\hat{\mathbf{p}},D))^2\right]=\sum_{ij}\frac{\partial Y(\mathbf{p},D)}{\partial p_i}\frac{\partial Y(\mathbf{p},D)}{\partial p_j} \qquad \text{(A.2)}$$

The derivatives are calculated numerically:

$$\frac{\partial Y(\mathbf{p},D)}{\partial p_i} \approx \frac{Y(\hat{\mathbf{p}}+\Delta p_i \mathbf{e}_i, D) - Y(\hat{\mathbf{p}},D)}{\Delta p_i} \tag{A.3}$$

with $\mathbf{e}_i$ being a unit vector in the direction of p_i. The step sizes Δp_i are chosen according to Eq. A.16 as for fitting.

A.2.5.3 The Meteorological Data

Hourly values are generally sufficient for long term prediction. However, during each timestep of simulation the load and auxiliary settings shall be constant. If necessary, timesteps as given by the meteorological data must be split.

The ambient temperature T_{ca}, the solar irradiance G_t and the wind velocity in collector plane (option W_{fit} only) have to be provided from Test Reference Year (TRY) data[12].

For converting the measured values G_b (normal incidence direct irradiance) and G_d (horizontal diffuse irradiance) to the irradiance on collector plane G_t with tilt angle β (zero for horizontal) and azimuth angle γ (zero for facing the equator, positive east), the following algorithm shall be used according to Hay and Davies as reported in [10]:

$$G_t(\beta,\gamma) = G_b\cos(\theta)\left[1+\rho\sin^2\left(\tfrac{\beta}{2}\right)\right] + G_d\left[\tau\frac{\cos(\theta)}{\sin(h)} + (1-\tau)\cos^2\left(\tfrac{\beta}{2}\right) + \rho\sin^2\left(\tfrac{\beta}{2}\right)\right] \tag{A.4}$$

Here, ρ is the albedo of the earth's surface, h is the solar elevation angle, θ is the angle between the collector normal and the solar beam direction, and τ is a measure of the quasi-direct fraction of G_d, which is estimated by the atmospheric transmission for direct radiation:

$$\tau = \frac{G_b}{\left[1-0.0334\sin\left(\frac{2\pi}{365}(N-81)\right)\right]I_0} \tag{A.5}$$

Here, I_0 is the solar constant, $I_0 = 1367\ \mathrm{Wm^{-2}}$, and N is the day of the year (N =1 for first of January). The albedo ρ shall be set to 0.2.

A.2.5.4 Operational Data

A.2.5.4.1 The Load

The load capacitance rate $\dot{C}_L$ (or hot water flow) as function of time has to be taken into account in the simulation. For each timestep $\dot{C}_L$ must be constant. A fixed demand temperature T_D and a fixed mains temperature T_{cw} shall be used.

A.2.5.4.2 Ambient Temperature of the Store

The ambient temperature of the store shall be either

a) equal to the collector ambient temperature (e.g. for closely coupled systems), or

b) constant for systems with the store inside the building (e.g. in the cellar).

---

12) Available are e.g.: European data [8], german data from [9].

A.2.5.4.3 Wind Velocity (Option W_{fit} only)

The wind velocity in collector plane shall be taken as 0.35 times the meteorological wind velocity[13].

A.2.5.4.4 Auxiliary (Systems with integrated auxiliary only)

The simulation shall take into account a set temperature T_{set} and a maximum auxiliary power $P_{aux}^{\max}$ as function of time (e.g. continuous or peak-off mode). During each timestep the settings must not change.

Systems may fail to meet the required load temperature T_D in the case of intermittent operation or finite available power. In the case of failure (minimum store temperature $T_S^{\min} < T_D$), the set temperature T_{set} shall be increased. If $T_S^{\min}$ is significantly above T_D, T_{set} shall be decreased in order to avoid unnecessary stand by losses.

A.2.5.5 The LTP Summary

The long term performance is expressed as the system gain Q_{net},

$$Q_{net} = \int P_{net} \mathrm{d}t = \int \left(\dot{C}_L \left(T_L - T_{cw} \right) - P_{aux} \right) \mathrm{d}t \qquad \text{(A.6)}$$

A.3 The Algorithm of Dynamic Fitting

A.3.1 Dynamic Modelling

Let *y* be some system variable accessible to measurement, e.g. the output power of a water heating system. Let a model of a test system predict the value of y as a function of time by a differential equation for the system state **z**, which generally cannot be measured in detail.

$$\frac{\mathrm{d}\mathbf{z}}{\mathrm{d}t} = \mathbf{f}[\mathbf{p}, \mathbf{z}(t), \mathbf{e}(t)], y(t) = h[\mathbf{p}, \mathbf{z}(t), \mathbf{e}(t)] \qquad \text{(A.7)}$$

Alternatively, the system may be described by a partial differential equation:

$$\frac{\partial \mathbf{z}(t,x)}{\partial t} = \mathbf{f}[\mathbf{z}(t,\cdot), \mathbf{p}, \mathbf{e}(t)](x), y(t) = h[\mathbf{p}, \mathbf{z}(t,\cdot), \mathbf{e}(t)] \qquad \text{(A.8)}$$

where *x* represents for example the height in the store.

Here **p** represents a set of constant parameters and **e**(*t*) the input variables at time t, e.g. meteorological data and the draw off mass flow. Only y(*t*) and **e**(*t*) are assumed accessible to measurement. The system state **z** represents e.g. the temperature distribution inside the store.

---

[13] This factor results from the expression $\left(\ln(h_2/u_2)/\ln(h_0/u_2)\right)/\left(\ln(h_1/u_1)/\ln(h_0/u_1)\right)$ where h_0 = 60 m, h_1 = 10 m the height where the meteorological measurement is taken, u_1 = 0.03 m the corresponding ambient roughness, h_2 = 3 m the (effective) height where the collector is installed, u_2 = 1 m the corresponding ambient roughness, see [11].

A.3.2 Parameter Identification

For a set of measured sequences $S_m = \left\{y^{\exp}(t), \mathbf{e}(t)\right\} t \in \left[t_m^0, t_m^1\right]$, the observed system output $y^{\exp}(t)$ is compared with the model prediction y(**p**,t). The residual error function r(**p**,t),

$$r(\mathbf{p},t) = y^{\mathrm{mod}}(\mathbf{p},t) - y^{\exp}(t) \qquad \text{(A.9)}$$

includes measurement uncertainties of $y^{\exp}$ and **e** as well as the model error. It is measured by the objective function

$$C(\mathbf{p}) = \sum_{m} \sum_{\nu=0}^{\infty} F_{m\nu}^2 \left|\tilde{r}_{m\nu}(\mathbf{p})\right|^2 \qquad \text{A.10)}$$

which is a least-squares error function in the frequency domain. Here $\tilde{r}_{m\nu}(\mathbf{p})$ is the discrete cosine transform of r(**p**,t) over the sequence S_m:

$$\tilde{r}_{m\nu}(\mathbf{p}) = \left(\frac{2-\delta_{\nu 0}}{L_m}\right)^{\frac{1}{2}} \int_{t_m^0}^{t_m^1} r(\mathbf{p},t) \cos\left(\frac{\pi\nu\left(t-t_m^0\right)}{L_m}\right) dt \qquad \text{(A.11)}$$

A lowpass filter with gaussian shape,

$$F_{m\nu}^2 = \exp\left(-\left(\omega_\nu \tau_F\right)^2\right), \omega_\nu = \frac{2\pi\nu}{2L_m} \qquad \text{(A.12)}$$

is used with time constant τ_F.

The purpose of introducing a filter is to damp the influence of transients in the residue on the estimated values of the parameters. Such transients might be caused e.g. by inertia of the temperature sensors or errors in the modelling of stratification. The use of a low pass filter reflects the fact that transients in the energy yield with zero mean do not influence long term performance.

The value of the vector $\hat{\mathbf{p}}$ which minimizes C(**p**) is identified as the set of parameters which characterizes the tested system.

As a measure of the model error, the root mean square of the filtered residue is introduced:

$$c(\mathbf{p}) = \left(\frac{C(\mathbf{p})}{\sum_m F_{m0}^2 L_m} \right)^{\frac{1}{2}} \qquad \text{(A.13)}$$

A.3.2.1 Error Analysis

The statistical accuracy - i.e. the covariance matrix - of the parameters found by minimizing $C(\mathbf{p})$ is inferred from linearizing the model around $\hat{\mathbf{p}}$. Then, an error $\Delta\tilde{r}$ yields an error $\Delta\hat{\mathbf{p}}$:

$$\Delta\tilde{\mathbf{p}} = \mathbf{H}^{-1} \sum_{mv} F_{mv}^2 \Delta\tilde{r}_{mv} g_{mv}, \mathbf{H} = \sum_{mv} F_{mv}^2 g_{mv} g_{mv}^T \qquad \text{(A.14)}$$

where g_{mv} is the derivative of $\tilde{r}_{mv}$ with regard to **p**. The derivatives g_{mv} are calculated by one-sided difference quotients:

$$g_{mvi} = \frac{\partial \tilde{r}_{mv}(\mathbf{p})}{\partial p_i} \approx \frac{\tilde{r}_{mv}(\mathbf{p} + \Delta p_i \mathbf{e}_i) - \tilde{r}_{mv}(\mathbf{p})}{\Delta p_i} \qquad \text{(A.15)}$$

with $\mathbf{e}_i$ being a unit vector in the direction of p_i. The step sizes p_i are chosen as

$$\Delta p_i = \pm 0.02 \min\left(\max\left(|p_i|, 1\right), p_i^{\max} - p_i^{\min}\right) \qquad \text{(A.16)}$$

The sign is chosen in order to move away from the rim of the feasible parameter range [$p_i^{\min}$, $p_i^{\max}$].

To estimate the covariance matrix $V_{ij} = E\left[\Delta p_i \Delta p_j\right]$, the following relations are assumed:

$$E\left[\Delta\tilde{\mathrm{r}}_{mv} \Delta\tilde{\mathrm{r}}_{m'v'}\right] = \delta_{mm'} \delta_{v,v'} S_{mv} \qquad \text{(A.17)}$$

Then:

$$\mathbf{V} = \mathbf{H}^{-1} \left(\sum_{mv} F_{mv}^4 S_{mv} g_{mv} g_{mv}^T \right) \mathbf{H}^{-1} \qquad \text{(A.18)}$$

Since generally S_{mv} is neither known nor accessible to measurement, it is assumed that S_{mv} is constant, S_{mv} = *S* (white noise assumption). Hence, it remains to determine *S*. Looking at the definition of C(**p**) in Eq. (A.10), *S* could be calculated as:

$$S_0 = \frac{C(\hat{\mathbf{p}})}{\sum_{mv} F_{mv}^2} \qquad \text{(A.19)}$$

However, S_0 tends to underestimate S in the case of little data, since $\hat{\mathbf{p}}$ partially follows the random fluctuations of the error signal. Following the discussion of Norton [12] in 5.3.3, an estimator for S which is unbiased is:

$$S = \frac{S_0}{1 - \frac{\mathrm{tr}\left(\mathbf{H}^{-1}\mathbf{K}\right)}{\sum\limits_{mv} F_{mv}^2}} \mathbf{K} = \sum_{mv} F_{mv}^4 g_{mv} g_{mv}^T \,. \tag{A.20}$$

Here, tr(**A**) is the trace of the matrix **A**, $\mathrm{tr}(\mathbf{A}) = \sum\limits_i A_{ii}$. Hence, the final expression is:

$$\mathbf{V} = \frac{C(\hat{\mathbf{p}})}{\sum\limits_{mv} F_{mv}^2 - \mathrm{tr}\left(\mathbf{H}^{-1}\mathbf{K}\right)} \mathbf{H}^{-1}\mathbf{K}\mathbf{H}^{-1} \,. \tag{A.21}$$

The covariance matrix is the appropriate measure of the uncertainty in the parameters. However, the representation by a variance vector Δp_i in conjunction with a correlation matrix R is used by the fit programs:

$$\Delta p_i = \sqrt{V_{i,i}}, R_{i,j} = \frac{V_{i,j}}{\Delta p_i \Delta p_j} \,. \tag{A.22}$$

This representation is equivalent to the covariance matrix. Note that the Δp_i are standard, not maximum errors, and do not contain systematic errors such as sensor misalignment. E.g. a wrong calibration constant for a pyranometer influences the value of the area parameter, but does not show up in the standard errors.

The covariance matrix is used to estimate the prediction error, see A.2.5.

A.3.2.2 Algorithm for Minimization

A suitable algorithm for minimum localization shall be used which reliably yields the global minimum. A numerical differentiation shall be used to evaluate the derivatives of $\tilde{r}(\mathbf{p})$ with regard to the parameters.

A.3.2.3 Time Variant Filter

The filter used in the objective function uses a constant filter coefficient τ_F. However, in a SDHW system, the typical time scale is not constant at all; it may vary from less than an hour (in the case of high $\dot{C}_L$) to several days (for $\dot{C}_L$=0). This makes it impossible to find a value for τ_F, which retains a significant filter effect as well as the information contained in the temperature profile during a fast drawoff.

To solve the problems due to the variations of the time scale, a time variant filter coefficient $\tau_F^{'}$ is introduced:

$$\frac{1}{\tau_F^{'}} = \frac{1}{\tau_F} + \frac{\dot{C}_L}{C_F} \,, \tag{A.23}$$

where C_F is a constant and may be set to a certain fraction of the thermal store capacity C_S. The filter coefficient τ decreases with increasing $\dot{C}_L$. E.g., for C_F = 0.1 C_S, the draw off profile will be taken into account with a resolution of about 10 of the store volume, whereas for C_F >> C_S, the draw off profile will be ignored.

The technique used to realize the time variant filter is the transformation of the time t into a generalized time μ, which will be called metric:

$$d\mu = dt + \tau_F \frac{d\dot{C}_L}{C_F} . \qquad \text{(A.24)}$$

By this special choice of μ, during all drawoffs the time is expanded.

The residual function *r'*(μ) for the sequence S_m is defined by:

$$r_m^{'}(\mu) = \frac{d}{d\mu} \int_{t(0)}^{t(\mu)} r_m(t) dt . \qquad \text{(A.25)}$$

So, the time variant filter results from the transformation $t \rightarrow \mu, r \rightarrow r'$ in Eq. (A.11).

A.4 Mathematical Description of the SDHW Model

Firstly, a system with an heat exchanger immersed at the bottom is described. This restriction is eliminated in Section A.4.3.2.

A.4.1 The Main Assumptions

Note: Because the fitting procedure will tune the model to the measured system data, it is not necessary that the SDHW model (or the assumptions on which it was built) is an exact representation of the system tested. For validation of the SDHW model and the test procedure see Annex B.

a) The state of the system at time t is characterized by the one-dimensional distribution *T(t,h)* of the store temperature, with the normalized height h in the range [0, 1], i.e. horizontal temperature gradients are neglected.
This assumption implies neglecting different effects such as convection caused by store losses as well as neglecting horizontal temperature gradients caused by the geometry of the solar loop heat exchanger.

b) The cold water is injected at height h = 0, the load is withdrawn at height h = 1. The remaining water in the store is shifted by an according value (plug flow).

c) The collector power is brought in at height h = 0 and is transported to water above by natural convection. This is equivalent to an heat exchanger with no vertical extension immersed at the bottom of the store.

d) The auxiliary power is brought in at height h = 1 - f_{aux} and is transported to water above by convection.

e) Local convection makes sure that $\partial T/\partial h \geq 0$ holds.

f) Mixing or heat conduction do not occur for $\dot{C}_S$ =0, except for fulfilling the relation mentioned above.

g) Cold water mixing is modelled by a diffusion term:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial h}\left(D \frac{\partial T}{\partial h} \right) \qquad \text{(A.28)}$$

h) It is assumed that the (time dependent) diffusion coefficient D is correlated with the load:

$$D(t) = D_L \dot{C}_S / C_S . \tag{A.27}$$

i) The loss coefficient is equally distributed over the height (dU_S /dh=0).

j) The heat capacity is equally distributed over the height (dC_S/dh=0). The capacity does not depend on the temperature (latent heat storage presumably can not be modelled this way).

A.4.2 The Partial Differential Equation

In the sequel a differential equation for the plug flow model is given for the special case of an heat exchanger immersed at the bottom of the store.

The solution might be obtained as limit of a set of parabolic partial differential equations for ε□→ 0:

$$\begin{aligned} C_S \frac{\partial T(t,h))}{\partial t} = {} & \delta_e(h) A_C^* \left[G_t^* - u_C^* (T - T_{ca}) \right]^+ \\ & + \delta_e(h - f_{aux}) P_{aux} \\ & - U_S (T - T_{sa}) \\ & + \dot{C}_S \left(-\frac{\partial T}{\partial h} + \delta_e(h)(T_{cw} - T) \right) \\ & + \frac{\partial}{\partial h} \left(D_L \dot{C}_S \frac{\partial T}{\partial h} \right) \\ & + \frac{\partial}{\partial h} \left(b \exp\left(-\frac{a}{\varepsilon} \frac{\partial T}{\partial h} \right) \frac{\partial T}{\partial h} \right) \end{aligned} \tag{A.28}$$

The meaning of the terms of the right side is: Collector gain, auxiliary power, store losses, plug flow, diffusion and convection.

The function δ_e is for ε → 0 a Dirac-distribution at zero:

$$\delta_e(x) = \begin{cases} \dfrac{e^{-x/\varepsilon}}{\varepsilon} & \text{for} x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{A.29}$$

Convection is modelled by a diffusion process with a diffusion coefficient depending on the temperature gradient (a and b are arbitrary positive constants). This makes sure that in the limit ε → 0 the requirement ∂ T/∂ h ≥ 0 is fulfilled exactly. Furthermore, with ε → 0 the heat exchanger, the cold water inlet and the auxiliary heater are modelled with zero extension.

A.4.3 Miscellaneous

A.4.3.1 Load Side Heat Exchanger

If a load side heat exchanger is used, the capacitance rate $\dot{C}_S$ is reduced by the factor $\phi(R_L\ \dot{C}_S)$, $\phi(x) = (1-e^{-x})/x$, see Fig. A.6.

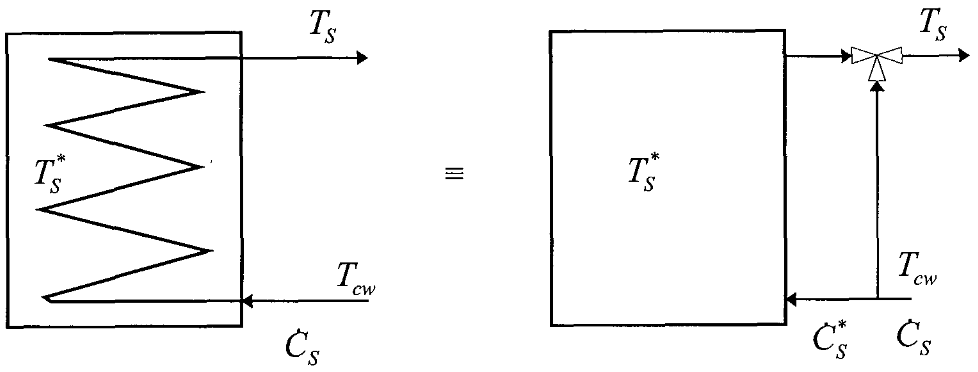


Figure A.6: Modelling of a load side heat exchanger. Within the model, the heat exchanger is replaced by a mixing valve outside the store. The capacitance rate through the store is $\dot{C}_S' = \dot{C}_S\ \phi(R_L\ \dot{C}_S)$,

A.4.3.2 External Collector Loop Heat Exchanger

An external heat exchanger is modelled by a direct collector loop with fixed capacitance rate $\dot{C}_C$:

$$\dot{C}_C = A_C^* u_C^* \big/ \left(1 - e^{-S_C}\right), \quad S_C > 0. \tag{A.30}$$

The height of the inlet is choosen such as to match the collector outlet and the according store temperature.

An immersed heat exchanger (S_C =0) is equivalent to $\dot{C}_C = \infty$.

A.4.4 Comparison with Other Simulation Models

A.4.4.1 TRNSYS

For $D_L = 0$, the model is equivalent to the simulation program TRNSYS [7] using the linear collector model, small temperature differences for the controller, variable collector inlet position and the plug flow tank (type 38) with:

- zero internal heat conduction.
- zero losses at the bottom and top of the store.

For D_L >>1 and S_C = 0, the type 4 store with one node (fully mixed) is equivalent.

Intermediate values of D_L cannot be represented by `TRNSYS` standard modules.

A.4.5 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 standard. 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 diskette from [16 (DIN)]. A description of the system model is given in table A.3.

System:	forced-circulation type
Collector:	collector aperture area: 5 m^2 optical efficiency: η_0= 0.8 collector heat loss coefficients: a_1 = 3.5W/(m^2 K), a_2 = 0.02W/(m^2K^2) collector heat capacity: 7 kJ/(m^2 K) inc. angle modifier coeff.: $K_{\tau\alpha}(50°)$ = 0.92
Collector Loop:	flow-rate: 60 l/h (low flow) pump switch-points: ΔT_{on} = 10 K, ΔT_{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 eff. vert. heat conductivity 2 x λ_{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 aux. heated part: 135 l

Table A.3: Model parameters of the reference system

The set of measuring data shall be evaluated according to the procedure described in clause 7.

The long term performance prediction shall be carried out as specified in clause 8 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 compatibility of the specific model and parmeter identification implementation is considered as compatible with the definitions outlined in this annex when the predicted long term performance is within the specified range.

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

A.4.6 Nomenclature (Specific for Annex A)

Symbol	**Units**	**Meaning**
c	[W]	Normalized objective function
C	[W^{2}s]	Objective function to be minimized
$\dot{C}_C$	[WK^{-1}]	Thermal capacitance rate in the collector loop
$\dot{C}_L$	[WK^{-1}]	Thermal capacitance rate at the load
$\mathbf{e}$		System input variables
E(x)		Expected value of x
$\mathbf{f}$		Total time derivative of $\mathbf{z}$ as a function of $\mathbf{z}(t)$, $\mathbf{e}(t)$, t
$\mathbf{H}$		A matrix which approximates the second derivative (Hessian matrix) of C
L_m	[s]	Length of the m'th sequence
m	[-]	Index numbering the measured sequences
$\mathbf{p}$		Parameter vector
$P_{aux}^{\max}$	[W]	Maximum auxiliary power available
$P_C(T)$	[W]	Collector loop power for inlet temperature T
$r(\mathbf{p})$	[W]	Residual error function, $r(\mathbf{p}) = y^{\text{mod}}(\mathbf{p}) - y^{\text{exp}}$
$\tilde{r}_m$		Cosine transform of r over the interval I_m
$\boldsymbol{R}$	[-]	Parameter correlation matrix
$\mathbf{s}$		Standard deviations of the parameters
S_m		Sequence number m over the time interval $\left[t_m^0, t_m^1\right]$
t	[s]	Time
t_m^0		Begin of the m'th sequence
T_L	[°C]	Temperature of the water delivered to the user $(T_L \leq T_S)$
T_D	[°C]	Temperature demanded by the user
T_{set}	[°C]	Set temperature of the auxiliary heater controller
V		Estimated covariance matrix of the paramters $\mathbf{p}$

y^{mod}		Modelled system output
y^{exp}		Measured system output
$\mathbf{z}$		System state vector
$\frac{d}{dx}$		Total derivative with respect to x (x: scalar or vector)
$\frac{\partial}{\partial x}$		Partial derivative with respect to x (x: scalar or vector)
$[x]^{+}$		Yields x for $x > 0$, otherwise 0.
$\forall_x F(x)$		All x satisfy the relation $F(x)$
δ_{ij}	[-]	Kronecker symbol; $\delta_{ij} = 1$ for $i = j$, otherwise $\delta_{ij} = 0$
Δr		Measurement error in $\tilde{r}$
v	[-]	Frequency; cycles per (double) interval
Δt_{skip}	[s]	Skip time (see A.2.3)

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/(m²K), a_2 = 0.04 W/(m²K²) and with an incident angle dependency for solar irradiance limited by the following equation: $K_{\tau\alpha} = 1-[\tan(\theta/2)]^{1/r}$ with $r < 0.4$. Notice that test data for systems with higher incident angle dependency may be processed using corrected solar irradiance (see footnote no. 3 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 ([17], [18]).

Note: the list in clause B.1 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 1.1.

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 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 into different directions[14].

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 table 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 table C.2.3. If no design load is specified, a load from table 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.

---

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

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: ....

- 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

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 (see footnote 3 of 1.4) ....

....

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	
1000	
1500	

*: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		45 °C

temperature is exceeded, mains water is mixed to achieve T_D)		
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}		see clause 5.1.6.1
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

Following set of instruments and sensors is recommended for solar domestic hot water (SDHW) system:

- *Irradiance:* Standard class 1 pyranometer.
- *Collector ambient temperature:* Ventilated, double shielded RTD thermometer or calibrated Ics thermocouples.
- *Store ambient temperature:* Standard RTD thermometer or calibrated Ics thermocouples.
- *Wind velocity:* Cup anemometer.
- *Fluid temperature:* Very small four wire Pt100 RTD in stainless steel tube, diameter no more than 2 mm; commercial fluid mixing device.
- *Volume flow:* Piston ring flow meter or magnetic-inductive flow meter with electrical pulse output.
- *Electrical power:* Commercial electricity meter with electrical pulse output.

Note: A detailed description of this set of instruments and a data acquisition program is available from [15].

D.2 Measuring the Thermal Energy Drawn from a Hot Water Store

In this section,

- 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 must comply with the manufacturer's instructions.
    - The thermal time constant of the temperature sensors can lead to large errors and must 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 the following.

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 anologous 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}:

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

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

Eqn. D.1 is equivalent to

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

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

The power P_L or energy Q_L delivered by a hot water store must 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 it must be defined more clearly what is meant by $\dot{m}$, T_{in} and T_{out}.

$\dot{m}_{in}$ 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 dm_{out} from T_{in} to T_{out}:

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

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

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

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 two percent.

D.2.2 Measurement of the Mass Flow Rate $\dot{m}_{out}$

In general it is not possible to measure $\dot{m}_{out}$ directly, because the customary flow meters are volume flow meters.

If the volume flow meter is capable to withstand 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

$$Q_L = \int_I \rho(T_{out})\dot{V}_{out}\bar{c}_p(T_{in},T_{out})\cdot(T_{out}-T_{in})\,dt \qquad \text{(D.5)}$$

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 dV_S during the time interval d*t* due to thermal expansion of the store material. Then holds:

$$\mathrm{dV_{in}} = \mathrm{dV_{out}} \qquad \text{(D.6)}$$

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

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

where α denotes the linear expansion coefficient of the store material. The change of store volume dVs is given by

$$dV_S = 3\alpha d\overline{\theta}_S V_S^0 \approx 3\alpha\left(T_{out} - T_{in}\right)dV_{in} \qquad \text{(D.8)}$$

Now the mass dm_{out} drawn from the store is given by:

$$dm_{out} = \rho(T_{out})dV_{in}\left(1 - 3\alpha\left(T_{out} - T_{in}\right)\right) \qquad \text{(D.9)}$$

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

$$Q_L = \int_I \underbrace{\underbrace{\rho(T_{out})\dot{V}_{in}\left(1 - 3\alpha\left(T_{out} - T_{in}\right)\right)}_{\dot{m}_{out}}\bar{c}_p\left(T_{in},T_{out}\right)}_{\dot{C}_L}\cdot\left(T_{out} - T_{in}\right)dt \qquad \text{(D.10)}$$

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[15] 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.

---

[15] $\alpha = 2 \cdot 10^{-5}\ \mathrm{K}^{-1}$

Therefore, Eq. D.10 can be simplified to

$$Q_L = \int_t \underbrace{\underbrace{\rho(T_{out})\dot{V}_{in}}_{\dot{m}_{out}}\bar{c}_p(T_{in},T_{out})}_{\dot{C}_L}\cdot\left(T_{out}-T_{in}\right)dt \qquad \text{(D.11)}$$

In Eq. 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 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 must 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, Eq. 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

$$Q_L = \int_t \rho(T_{in})\,\dot{V}_{in}\bar{c}_p\left(T_{in},T_{out}\right)\left(T_{out}-T_{in}\right)dt \qquad \text{(D.12)}$$

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 a 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 must be tested with the pressure conditions recommended by the manufacturer; a non-pressurised test of a normally pressurised 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 be not 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_{out} - T_{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 body of this standard)

- The sensors should have low thermal inertia. This can be reached through using thermocouples or small RTD's and avoiding unnecessarily short drawoff intervals.
- 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 e.g. 60 s of drawoff with reduced flow rate to reduce the power at those times when the error of the temperatures is large.

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 $\rho(T_{out})$ and $\bar{c}_p$ (T_{in}, T_{out}) 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:

$$\begin{gathered}\rho(\theta) = \left(1000.67 - 7.3845 \cdot 10^{-2}\,{}^\circ\mathrm{C}^{-1}\theta - 3.547 \cdot 10^{-3}\,{}^\circ\mathrm{C}^{-2}\theta^2\right)\frac{\mathrm{kg}}{\mathrm{m}^3} + \Delta\rho \\ |\Delta\rho| < 0.8\frac{\mathrm{kg}}{\mathrm{m}^3} \qquad |\Delta\rho| < 0.5\frac{\mathrm{kg}}{\mathrm{m}^3}\ \text{for}\ \theta > 3\,{}^\circ\mathrm{C}\end{gathered} \qquad \text{(D.14)}$$

$$\bar{c}_p(\theta_1,\theta_2) = \left(4.20028 - 5.048 \cdot 10^{-4}\,{}^\circ C^{-1}(\theta_1 + \theta_2) + 4.097 \cdot 10^{-6}\,{}^\circ C^{-2}\left((\theta_1 + \theta_2)^2 - \theta_1\theta_2\right)\right)\frac{\mathrm{kJ}}{\mathrm{kgK}} \qquad \text{(D.15)}$$

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

Annex E

(informative)

Bibliography

[1] W. Spirkl und J. Muschaweck. General Model for Dynamic Testing of Solar Domestic Hot Water Systems. *Solar Energy Materials & Solar Cells*, 28:93 - 102, 1992.

[2] InSitu Scientific Software. Dynamic System Testing Program (Version 2.6). ISS, Kriegerstr. 23 d, D-82110 Germering, Fax +49 89 427778, FRG, 1996.

[3] B.A. Rogers. Recommendations on Test Procedures for the Thermal Performance of Solar Domestic-Hot-Water Heating Systems. Technical Report SEU-IEA-TR3, International Energy Agency (IEA), 1989.

[4] W. Spirkl. Dynamic SDHW Testing. J. of Solar Energy Eng., Transactions of the ASME, 112:98--101, 1990.

[5] W. Spirkl. Dynamische Vermessung von Solaranlagen zur Warmwasserbereitung. Fortschrittsberichte der VDI-Zeitschriften, Reihe 6: Energietechnik, Nr. 241, VDI-Verlag, Düsseldorf (W-Germany), 1990. ISBN 3-18-14 4106-6.

[6] Dynamic Testing of Solar Domestic Hot Water Systems. Technical Report EUR 11606 EN, International Energy Agency, 1992.

[7] S.A. Klein, W.A. Beckman und P.I. Cooper. TRNSYS: A Transient System Simulation Program, Version 13.1. Solar Energy Laboratory, Madison Wisconsin, 1990.

[8] Cenergia Energy Consultants. Sct. Jacobs Vej 4, 2750 Ballerup, DK.

[9] Fachinformationszentrum Karlsruhe (FIZ), D-76344 Eggenstein-Leopoldhafen, FRG.

[10] D.T. Reindl, W.A. Beckmann und J.A. Duffie. Evaluation of Hourly Tilted Surface Radiation Models. Solar Energy, 45:9--17, 1990.

[11] J. Wieringa. An Objective Exposure Correction Method for Average Wind Speeds Measured at a Sheltered Location. Quart.J.R.Met.Soc., 102:241--243, 1976.

[12] J.P. Norton. An Introduction to Identification. Academic Press, 1986.

[13] K. Blümel, E. Hollan, M. Kähler und R. Peter. Entwicklung von Testreferenzjahren (TRY) für Klimaregionen der Bundesrepublik Deutschland. Forschungsbericht BMFT-FB-T 86-051, Freie Universität Berlin, 1986.

[14] G.L. Morrison und A. Litvak. Condensed Solar Radiation Data Base for Australia. Technical Report FMT/1, University of New South Wales, Sydney Australia, 1988.

[15] Zentrum für angewandte Energieforschung Bayern (ZAE). Postfach 440254, D-80751 München.

[16] DIN e.V. NHRS. E. Memmert. Postfach 1107, D-10787 Berlin.

[17] H. Visser, Th. Pauschinger, B. Perers, P. Isakson (Editors). Dynamic Testing of Active Solar Heating Systems, Final Report of the IEA Solar Heating and Cooling Task 14 Dynamic Component and System Testing Subtask, IEA Report No. T.14.DCST.1A&B, Delft, April 1997

[18] Th. Pauschinger, H. Drück. VELS II, Verfahren zur Ermittlung der Leistungsfähigkeit von Solaranlagen. Final Report. Universität Stuttgart, Institut für Thermodynamik und Wärmetechnik, November 1995.

Bibliography

[1] EUR 9765, CEC:1985, Test Reference Years TRY — weather sets for computer simulations of solar energy systems and energy consumption in buildings

[2] ISO 9459-2:1995, Solar heating — Domestic water heating systems — Part 2: Outdoor test methods for system performance characterisation and yearly performance prediction of solar only systems

[3] TNO Report 93-BBI-R1456, Description of the Dutch outdoor (DST) test method for solar domestic hot water systems