Dynamic Testing of Active Solar Heating Systems

Summary Report of the IEA Task 14 Dynamic Component and System Testing Subtask

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SHORT INTRODUCTION

This report summarizes the work of the Dynamic Component and System Testing (DCST) Subtask within Task 14 of the IEA Solar Heating and Cooling Programme. The DCST Subtask was incorporated in Task 14 on Advances Solar Energy Systems in 1993 after completion of the Dynamic Systems Testing Group (DSTG), a remote working group within Task 14. The DSTG work was continued and extended in the DCST Subtask.

The DCST Subtask consisted of three different Groups. Each Group was involved in one or more subjects. Groups and major subjects were:

-	Group I:	Dynamic Collector Testing.
-	Group II:	Dynamic Solar Domestic Hot Water System Testing.
-	Group III:	Component Testing and System Simulation of Small Solar Heating Systems. and In Situ Testing of Solar Heating Systems.

The Final Report of the DCST Subtask will describe in detail the work carried out and the results of that work. There will be two Volumes: Volume A with the work of Groups I and III, and Volume B with the Group II work. The present report gives summaries of the work written by the Group leaders. It should be noticed that these summaries still have to be approved by the DCST Subtask participants.

Dynamic Collector Testing - Summary by Bengt Perers

OBJECTIVE

The aim of the work within IEA SH&C Task 14 has been to give a scientific basis for an update of the present stationary collector test standard ISO 9806-1 to extend the test method also to non stationary all day outdoor climate and operating conditions. Close connections to both CEN and ISO has been kept through the National Testing and Research institute, SP, in Sweden. The backwards compaibility to existing standards has turned out to be an important point to speed up the introduction of dynamic collector testing.

Some of the main advantages that are looked for is a shorter and less expensive outdoor test and at the same time a much more complete characterisation of the collector in a single test procedure.

An important goal has been to also include annual performance prediction as an integral part of the method. The same collector model and identified parameters from the test should be possible to use in a simulation programme for the extrapolation to the long-term performance.

SCOPE

Dynamic testing is a rapidly expanding filed with many new possibilities. The increasing availabilty of fast PC computer has made it possible to use much more testdata also from non stationary outdoor conditions in a standard test.

The solar collector work within IEA Task 14 has been focused on models and methods that can be used to improve standard collector testing. Several collector models starting from the present stationary collector test standard ISO 9806-1 and different parameter identification methods has been investigated. One of the main limitations in the method turned out to be the backwards compatibility to existing standards that finally decided what collector models that presently could be chosen and recommended for standard testing.

ACTIVITIES

1. Solar Thermal Collector models

There are a number of collector models that differ significantly in the individual sub models of the collector to take into account different second or third order effects more accurately and also with the aim to model the collector output at very short time steps and steps in inlet temperature and flow rate.

Still all the collector models agree in the common general structure as zero loss efficiency, heat loss coefficient, and thermal capacitance correction. The collector models with the more advanced heat loss models need the iterative DF parameter identification programme. Whereas the extended ISO model with correction terms can be evaluated with standard Multiple Linear Regression.

There are three main collector models that has been used in this work. The extended ISO model, the MFC model and the Dyncoll model. For comparison we start with the collector model options in ISO 9806-1.

The ISO 9806-1 model

For comparison we start to describe the present stationary ISO model used in the standard ISO 9806-1 This model has been widely used both in testing and for simulation. The basic equation is a stationary model for near normal incidence angle operation. The nomenclature is given in the next section.

$$q_u = F'(\tau\alpha)_e \, G_b \;-\; F'U_0 \, \Delta T \;-\; F'U_1 \, (\Delta T)^2 \qquad (6.1)$$

The insolation is denoted G_b to point out that only high insolation levels are accepted in the test sequence with low diffuse fraction. No correction for non stationary conditions is made so very stable inlet and radiation conditions are needed for each test point. Furthermore it is assumed that the incidence angle is normal so that incidence angle effects can be neglected. This resticts the measuring time very much during normal weather conditions except for very sunny climates.

In the ISO 9806-1 standard there are optional test procedures also for the determination of incidence angle dependence of the zero loss efficiency and the effective thermal capacitance of the collector. The full instantaneous equation from all the options in the ISO standard can be written:

$$q_u = F'(\tau\alpha)_e \, K_{\tau\alpha b}(\theta) \, G_b \;-\; F'U_0 \, \Delta T \;-\; F'U_1 \, (\Delta T)^2 \;-\; (mC)_e \, dTm/dt \qquad (6.2)$$

Note that this is a clear weather or indoor simulator model as the solar radiation is treated as beam radiation. No correction term for diffuse radiation is proposed in the standard. In most simulation programmes the solar radiation is divided into beam and diffuse radiation and a separate incidence angle correction is added for diffuse radiation. This correction term is often derived from the incidence angle dependence for beam radiation of the collector. Therefore a complete ISO test gives this information for standard simulation purposes but the cost would be much higher than one dynamic test giving all parameters at the same time.

The Extended ISO model

This model is basically the same as the ISO model but with some extra correction terms for diffuse radiation, wind speed, sky temperature and wind dependence in the zero loss efficiency (i.e. unglazed rubber collectors). A correction term is also given if the inlet and outlet sensors can not be mounted close enough to the collector. Such temperture losses should of course be avoided in laboratory testing. All the ISO and extended model parameters can be identified with Multiple Linear Regression as well as with DF. The sub models in this equation has all been verified against measured data in other IEA SH&C activities as within IEA Task VI and Task III. They are also based on physics even if the detailed heat loss pattern of a solar collector is very complicated in detail mainly due to the convection heat flows.

$$\begin{aligned} q_u = {} & F'(\tau\alpha)_e \, K_{\tau\alpha b}(\theta) \, G_b + F'(\tau\alpha)_e \, K_{\tau\alpha d} \, G_d \;+ k_w \, G_{tot} \, w \;-\; F'U_0 \, \Delta T \;-\; F'U_1 \, (\Delta T)^2 \;- \\ & - F'U_w \, \Delta T \, w \;-\; F'U_{sky} \, \Delta T_{sky} \;-\; (mC)_e \, dT_f/dt \;-\; U_p \, \Delta T \qquad (6.3) \end{aligned}$$

q_u = Collector array thermal output [W/m^2]
$F'(\tau\alpha)_e$ = Zero loss efficiency for direct radiation at normal incidence. [-]
$K_{\tau\alpha b}(\theta)$ = Incidence angle modifier for direct radiation [-]
$K_{\tau\alpha d}$ = Incidence angle modifier for diffuse radiation [-]
G_{tot} = Global radiation onto the collector plane [W/m^2]
G_b = Direct radiation onto the collector plane [W/m^2]
G_d = Diffuse radiation onto the collector plane [W/m^2]

$F'U_0$ = Heat loss coefficient at $(T_m - T_a)=0$ $[W/(m^2*K)]$
$F'U_1$ = Temperature dependence of the heat loss coeff. $[W/(m^2*K^2)]$
$F'U_w$ = Wind speed dependence of the heat loss coeff. $[Ws/(m^3*K)]$
$F'U_{sky}$ = Sky temperature dependence of the heat loss coeff. $[W/(m^2*K)]$
U_p = Piping heat loss coefficient per m^2 of coll. $[W/m^2*K]$
$(mC)_e$ = Effective thermal capacitance including piping for the collector array. $[J/(m^2*K)]$
ΔT = Temperature difference $(T_m - T_a)$ [C]
ΔT_{sky} = Temperature difference $(T_a - T_{sky})$ [C]
w = Wind speed near the collector [m/s]
k_w = Wind dependence in the zero loss efficiency [m/s]
dT_f/dt = Mean time derivative for the average fluid temperature T_m within the time step. [K/s]
T_m = Mean fluid temperature in the collector $(T_{in}+T_{out})*0.5$ [C]
T_a = Ambient air temperature near the collector [C]
T_{sky} = Effective broadband sky temperature [C]
θ = Incidence angle for the direct solar radiation onto the collector plane [radians]

The MFC Matched Flow Collector model

The MFC Matched Flow Collector model has been developed by Per Isakson in Sweden. This model is very elaborated in the heat loss and thermal capacitance part. An elegant analytical solution has been found so that a distributed absorber model with local capacitance's and local U values that are temperature dependent can be handled without iterations within each time step. One of the main aims is to be able to model the heat losses more accurately at low flow conditions and rapid changes in inlet temperature when the temperature increase along the absorber flow path can be highly non-linear. Wind and sky temperature influence on the heat losses are also an option in the model. The optical part of the collector equation is prepared with a large number of standard options for the incidence angle dependence. The model is written as a TRNSYS component and the model parameters are identified with the external model option in DF. Per Isakson has also written a special interface between the MFC model and DF to speed up the parameter identification and also document each run in a systematic way. A more detailed description can be found in the MFC manual (Isakson 1994).

The DF Dyncoll collector model

Dyncoll: This is a multinode collector model that is distributed together with DF. The absorber is divided into a number of nodes along the flow path similar to Per Isaksons model but in this case no analytical solution is used. The focus is also here to take into account the temperature distribution along the absorber flow path. The optical part of the collector equation is the same as the ISO collector model except that the incidence angle dependence is described with the Ambrosetti equation and not the ASHRAE b0 function. The parameter identification is done with Dyncoll as an external model. A more detailed description can be found in the DF manual delivered together with the programme.

Finite difference and FFC Collector models for detailed simulation

Some work has also been done with a finite difference collector model and an FFC collector model to investigate the wind , sky temperature and thermal capacitance effects during a test with rapid changes in inlet temperature and solar radiation. It has been found that the back insulation of the collector gives a small additional very long time constant that none of the present collector models take into account. By avoiding or having symmetrical steps up and down in inlet temperature in the test sequence this small effect is taken care of. The effect could also be seen experimentally in the ISFH indoor test described in chapter 7.

2. *Parameter identification methods*

Two different parameter identification methods has been used within IEA Task 14. They have different application ranges and advantages.

The DF parameter identification method

An iterative search method using the DF program package specially developed for this purpose. The freedom in the collector model is very large. The identification method takes a significant time and theoretically there is also a possibility that the globally best parameter set is not found. This is addressed in the programme algorithm by making many new searches from different starting points and choosing the best parameter set. In practice this has not shown to be a problem with the more recent versions of the programme.

Of course also the systematic but at the same uncorrelated variation of the input parameters is a very important condition to find accurate parameter values. Basically the DF programme uses the iterative Levenberg Marquardt parameter identification method. This is a well known algorithm that can be programmed from for example numerical recipes in Pascal. But the DF programme has been developed and improved during more than five years and is now a general- purpose software with a lot of routines like pre-processing of data, plotting and long term prediction. The programme can be bought from In Situ Software in Munich.

The Multiple Linear Regression method

This is a non iterative very fast matrix method called Multiple Linear Regression MLR that is available in most standard programme packages as LOTUS, EXCEL or more specialised statistical programmes like MINITAB or SISS. Multiple Linear Regressions is a generalization of standard Linear Regression used to fit a straight line to data in two dimensions.

Linear does only mean that the model has to be written as a sum of terms with the parameters p_n as a multiplier in front of the terms. For example: $Yout = p_0 + p_1{*}f(x_1,x_2) + p_2{*}g(x_1, x_3, x_4) + p_3{*}h(x_2, x_5)$. The sub models f(x..) g(x..) and h(x..) in each term can be non-linear.

A special case of MLR has also been tested which makes it possible to identify the same parameter in different subsets of the database. This has made it possible to identify for example the zero loss efficiency angle by angle without the need to have an equation. The derived IAM results can be used directly in TRNSYS WATSUN or MINSUN. It has also been found that the heat loss factor can be identified in successive ranges of ΔT and two axis IAM values.

3. *Test sequence design*

During the work within IEA Task 14 it has become more and more evident that the uncorrelated variation of the different influencing factors as for example solar radiation, inlet temperature and incidence angle is very important to give accurate parameter values. This is much more important than the choise of parameter identification method. Even with the most advanced parameter identification method accurate parameter values can not be achieved with data that has not enough variability.

A test sequence has therefore been deisgned to give the required variability in a short testing time. Due to the requirement of backwards compatibility to stationary testing the most advanced possibilities with rapidly varying inlet temperature has to be left out so that both stationary and dynamic data can be derived from the same test sequence.

The exact duration of the test is determined by the weather and can mno t be predicted exactly. In practice it has tur'ned out that the dynamic test normally takes about half the time, 2 weeks, instead of 1 month in the middle european climate.

4. Check of measured data

A check of the measured data is needed both to identify problems with the measurements but also to determine if enough data is available for an accurate parameter identification. As mentioned above the weather determines when enough data is available and has to be determined from test to test.

Check for errors in the measured data

A very efficient check of errors in the data can be made by using a preliminary guessed parameter set for the test object as input to the collector model. By plotting the measured collector output against this preliminary expected output, errors both in the collector operation and the measurement system can be detected as outliers form the expected relation. This method is very efficient as all relevant measured quantities are used intensively in the model and measured output.

5. Experimental results from indoor and outdoor testing

For routine testing purposes it has turned out that the difference is very small between the different models and methods. The collector parameters that are common with the stationary ISO collector model also comes out the same if a test is extended so that also stationary test points can be derived from the test period.

Therefore the MLR method with a modification of the ISO(Tm) collector model used in the present stationary test standard is sufficient for a wide range of collectors and is presently used by the Swedish National Testing and Research Institute for routine collector testing. Correction terms are added for thermal capacitance, wind speed, thermal sky radiation etc. but basically the collector equation is the same as in the present ISO standard with Tm =(Tout+Tin)*0.5 as the reference temperature. The separate test for incidence angle modifiers and thermal capacitance can now be integrated into a single dynamic test.

5. Measurement specifications

A special document about mesuarement specifications has also been written to define a common basis for measurements under non stationary conditons. An example of a special requirement is a high sampling frequency of the solara rasdiaotion to give true meanvalues under nonstationsyr irradiation conditions. The mounting of sensors is also more critical when using all day data. The extra requiremnts are easily met by professional equipment used today and will also improve the accuracy of standard stationary testing.

6. Standardisation

A proposal to ISO about dynamic collector testing has been given by the Swedish National Testing and Research Institute. The proposal has been accepted as a work item within ISO. The next step will be a proposal for a test procedure that will be written by the same institution in close co-operation with the IEA Task 14 experts.

The same procedure is now going on within the European standardisation organisation CEN and a draft test proposal is ready and a validation of the proposed method by national testing institutes is the final step.

Both proposals are put up as extension to the present ISO 9806-1 standard and not a separate new standard to speed up the process and also due to the fact that the test equipment and procedure can be the same in many respects.

CONCLUSIONS AND RECOMMENDATIONS

The main advantages with dynamic collector testing is a shorter and less expensive outdoor test and at the same time a much more complete characterisation of the solar collector in a single test procedure.

Important effects for the all day performance as for example influence of diffuse fraction, incidence angle, flowrate, wind speed, thermal sky radiation and thermal capacitance are taken into account.

The more complete characterisation of the collector also leads to less restrictions on the collector designs that can be tested and a wider range of collectors will be covered in the same dynamic test method.

All common collector designs from unglased swimmingpool collectors to concentrating high temperature collectors can now be tested with the same method. A vailidation of this wide range is still needed for standardisation purposes, but on a research level the method alreday has vbeen verified for this range.

The method also includes longterm performance prediction as an integral part of the method. The same collector model and identified parameters from the test are used in a simulation programme for the extrapolation to the long-term performance. This minimises the error in long-term performance prediction.

Only minor changes and refinements in the test equipment are required. By using all day data a much more complete characterisation of the collector can be derived in the one short test as one does not have to wait for stationary clear sky conditions to get useful test data.

To give representative long-term results the test sequence has to be specified so that a full varaiability in all important normal operating conditions are encountered during the test. This is done similar to the present stationary standard by a systematic variation of the inlet temperature to the collector within the design range of the collector.

It has been found that the back insulation of the collector gives a small additional very long time constant that none of the present collector models take into account. By avoiding or having symmetrical steps up and down in inlet temperature in the test sequence this small effect is taken care of.

The experiences from IEA Task 14 is now being forwarded to the collector testing groups within ISO and CEN. ISO has accepted dynamic collector testing as a work item. And a test proposal has been sent to CEN.

ACKNOWLEDGEMENTS

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Component Testing and System Simulation of Small Solar Heating Systems - Summary by Thomas Pauschinger

This report summarises the contribution of the IEA Task XIV Dynamic Component and System Testing (DCST) Group to a performance test method for solar heating systems by means of component testing and whole system simulation. The goal is the development of this test method for solar heating systems for hot water preparation and/or space heating and to establish a corresponding international test standard. The DCST group contributed to this work with scientific developments and investigations on the field of storage testing, the development of a test concept and the validation of the whole method by experimental tests.

1 Introduction

Several performance test methods for solar heating systems have been established as international standards or drafts within the international standard ISO 9459 (Part 1, Part 2, Part 3 and Part 5). All of these test methods are based on a **test of the whole system**, carried out either as indoor or outdoor test. This means the system is installed as a whole on a test stand for the necessary measurements.

Alternatively to these whole system test methods a test method by means of **component testing and whole system simulation** is proposed. In stead of the test of the whole system the system components, namely the collector, the store and the controller are experimentally tested. The performance prediction is then carried out by a computer simulation of the whole system, using a modular computer program such as TRNSYS /1/. In the following this method is called CTSS method, standing for *Component Testing - System Simulation.* Fig. 1 shows the structure of the CTSS method.

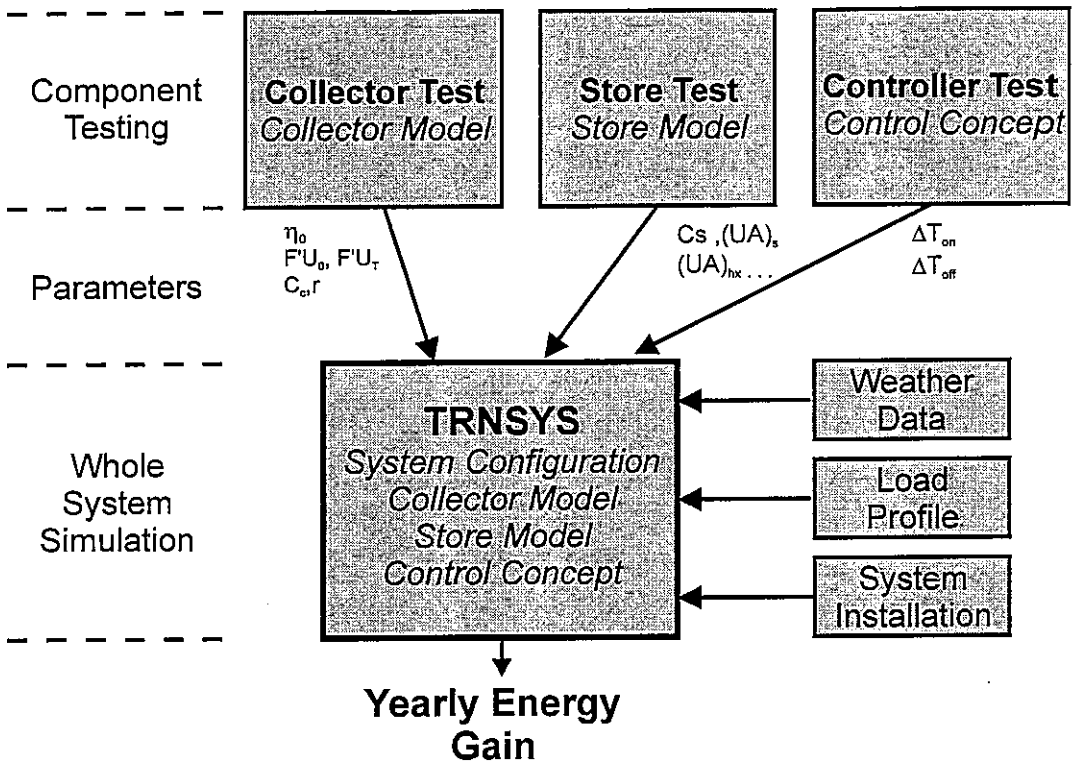


Figure 1: Procedure for testing solar heating systems with the CTSS method

The development of the CTSS method is motivated by several needs on the market and advantages over the whole system tests:

- The CTSS method is flexible with respect to exchanging and combining of the system components. A large part of the solar heating systems on the market are not offered in fix sizes. This means components can be alternatively chosen from an assortment of a company and can be combined in different sizes. The components can also be assembled in different system configurations e.g. to a system for domestic hot water preparation only or a system for combined domestic hot water preparation and space heating. For these types of systems a whole system test method would require the installation of all possible combinations and configurations on the test stand. Thus cost for testing would be high. With the CTSS method only the components are experimentally tested. The performance prediction for the whole system is performed with validated computer programs. Thus the CTSS method allows for more flexibility and cheaper testing.
- The CTSS method is currently the only test method that makes testing of systems for combined hot water preparation and space heating possible.

The need for a CTSS method was recognised already long time. However, none of the developments has been internationally harmonised and has reached the level of an internationally accepted test standard so far. The International Standardisation Organisation ISO has reserved Part 4 of ISO 9459 for a CTSS method. Recent activities in the European Committee for Standardisation CEN, based on the work of the DCST group, head for an appropriate test standard.

2 Goals of the DCST Group Work

The DCST Group originated in the IEA Dynamic System Testing Group (DSTG) /2/. During the work of the DSTG experience was gained on the field of modern methods for testing and simulating solar heating systems. Especially the numerical method of parameter identification was introduced for these purposes.

With this background the goal of the DCST Group was to contribute to the development and validation of the CTSS method by extending the application of this modern methods on component testing of collectors and stores and the synthesis of the component test results to a long term performance prediction for the whole system. The results shall form the scientific base for an international development of a test standard for the CTSS method as foreseen by the ISO technical committee ISO/TC 180 and now also adopted by the CEN technical committee CEN/TC 312.

The necessities identified for the development of the CTSS method were:

- A performance test method for stores of solar heating systems, which makes it possible to simulate the behaviour of the store in the whole system is needed. Of special interest is the application of the parameter identification method on store testing.
- The definition of a test procedure for the CTSS method.
- The reliability and accuracy of the method must be proved by experimental validation.

The development of an advanced collector test method was treated in Group I. No work has been carried out on the field of controller testing.

Important contributions to this work has come from LMU in Munich and ITW in Stuttgart. Results from Group I dealing with Dynamic Collector Testing were an important input to the CTSS method. The experiences gained from theoretical and experimental work were lively exchanged with the experts of Group II working on Dynamic System Testing and the experts of Group III working on in situ measurements of solar heating systems.

3 Development of a Test Method for Hot Water Stores

Testing of stores for solar heating systems as integral part of the CTSS method requires, that the test method delivers all relevant data for a simulation of the thermal behaviour of the store. Experience from many years of testing solar heating systems showed, that the accuracy of simulation results crucially depends on the compatibility of the test method and the simulation program. Dynamic testing as it was introduced with Dynamic System Testing and Dynamic Collector Testing opens the possibility to ensure a maximum compatibility between testing and simulation. This is reached by evaluating test data with parameter identification methods with appropriate numerical models and using then the same models with the obtained parameters for simulation.

The goal of the DCST Group was to deliver the scientific base for the development of a store test method based on dynamic testing. Following work was carried out:

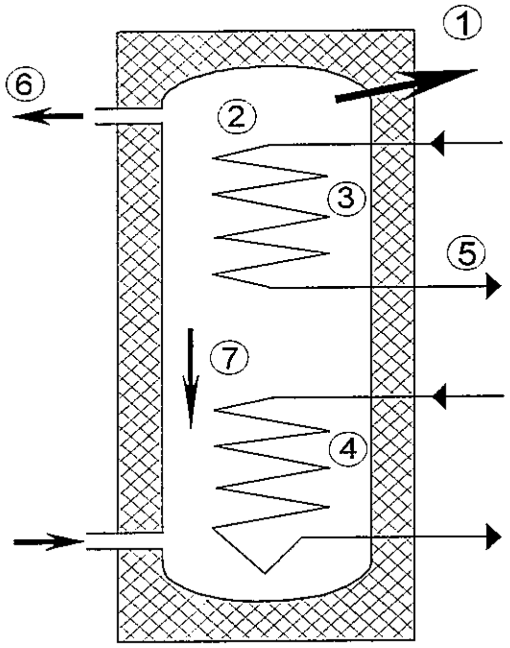
- Development of a store model for testing and simulation
- Definition of a test procedure for store testing
- Experimental investigations on the applicability of the store test method

Two models, the Multiport Model /3/ and a Plug-Flow Model /4/ were developed. Both were implemented as parameterized models in the simulation program TRNSYS so that they can be used for the process of parameter identification with the computer program DF /5/.

Measuring data are gained during tests, where the store is connected to a testing stand located in a laboratory with controlled ambient temperature. The testing stand consists of a charge and a discharge loop, which enables the thermal charging and discharging of the store according to well defined test sequences. During these tests the volume flow rates, all inlet and outlet temperatures of the store and the ambient temperature are measured and registered continuously. No measurements inside the storage are necessary.

Special test sequences were designed in order to stimulate the physical effects to be identified. The complete specifications for these test sequences can be found in /6/.

The basic store parameters that can be identified by this method are shown in figure 2. Parameters can be added or omitted depending on the store design.



① Heat loss rate

② Effective store volume resp. thermal capacitiy of the entire store

③ Heat transfer rate of the auxiliary heat exchanger

④ Heat transfer rate of the solar loop heat exchanger

⑤ Position of auxiliary loop heat exchanger resp. auxiliary volume

⑥ Thermal stratificaction during direct discharge —-> stratificaction number

⑦ Thermal stratificaction during stand-by —> effective vertical thermal conductivity

Figure 2: Thermal parameters of a store for solar heating systems

The store test method was up to now applied on 12 different stores. For several stores repeated tests were carried out in order to show the reproducibility of the test results.

In /7/ a very good reproducibility and accuracy of the test results are obtained for two different types of stores. For both stores a long term performance prediction was carried out using a standard solar heating system and the results obtained from the repeated store tests. In all cases the deviation of the solar fraction remained below ± 0.01.

The test method was also applied on data gained during a whole system test of a solar heating system with additional sensors at the store's in- and outlets.

In /4/ results from *detail tests* (only singular parameters result from a single test sequence) and *integrated tests* (a complete parameter set is identified from one test sequence) are compared.

The results of these investigations show that the method of *dynamic testing* represents a powerful tool also for testing stores for solar heating systems. The developed models and test procedure proved to be suitable for several types of stores.

The procedure as proposed by the DCST group was adopted by the technical committees of ISO and CEN. It is currently developed further by a group of experts within CEN TC 312 /8/.

4 Procedure for a CTSS Method

Apart from the advantages of the CTSS method mentioned above, there are also several risks with regard to the reliability of the test results. Since only the components are tested by real measurements, typical system failures (e.g. wrong placed sensors) might remain unrecognised. Also the system model for the long term performance prediction might not represent the behaviour of the real system. A concept for the whole test procedure must take this facts into account and should comprise, beside the specifications for component tests and the whole system simulation, also additional steps to ensure a sufficient reliability and accuracy of the test results (e.g. validation of the simulation models).

Following steps for the CTSS test procedure are proposed:

Step 1: The components collector, storage and controller are tested with a suitable test method.

Step 2: The function of the whole system is checked by inspecting all components and parts as well as the system documentation.

Step 3: The whole system is modelled using a simulation program for the relevant system configuration and the obtained component parameters. The yearly energy gain is predicted for reference conditions.

Step 4: If for the relevant system configuration no validated simulation model is available, then the model used for step 3 shall be validated by a test of the whole system, a so-called validation test.

In /9/ these steps are described more in detail. Reference is made to suitable test methods for the components (see Dynamic Collector Testing and the store test methods described in clause 2) and requirements on the whole system simulation are specified.

Following features of the test procedure are considered as important aspects for the reliability of the CTSS method:

- Very often the numerical models used in simulation programs are based on assumptions that are rarely or not known by the user of the program. The chosen input parameters, obtained from testing, might be entered in a wrong meaning leading to inaccurate results. The principle chosen for the CTSS method ensures a maximum compatibility by requiring the **same models for testing and simulation** (see figure 1).

- A **function check** of the whole system is carried out as step 2 of the CTSS procedure, prior to the whole system simulation. I.e. that all components and parts of the system as well as the system documentation are visually inspected with regard to typical system failures. Since in most cases the system is not installed as a whole, this step is important for detecting all failures that might not be recognised during the component tests.
- As step 4 the **validation of the simulation model** for the system performance prediction is adopted as integral part of the test procedure. For the validation of the simulation model the system is installed and tested as a whole. The measured and simulated thermal behaviour of the system is compared. Deviations shall remain below a certain required value. Such a validation is required only for new system configurations (i.e. hydraulic and control concept). Once a program is validated for a certain system configuration it can be used for all systems with the same configuration.
- Both the CTSS method and the whole system test methods will serve for testing certain types of systems. In many cases these methods will be used in parallel and must deliver comparable results. This was achieved by choosing the same **reference conditions** for the system installation (e.g. pipe length and insulation of the collector loop) and for the long term performance prediction (e.g. weather data, hot water load).

The procedure as proposed by the DCST Group was adopted by the technical committees of ISO and CEN. It is currently developed further by a group of experts within CEN TC 312 /8/.

5 The CTSS Method in Practice

Within the work of the DCST Group experience with the CTSS method was gained with typical forced-circulation systems for hot water preparation /9/. Eleven systems were tested:

- seven conventional systems with flat-plate collector
- two conventional systems with ETC
- one system with flat-plate collector and a store with stratifier
- one matched-flow system with CPC-ETC and external heat exchanger in the charge loop

For these systems a separate test of the collector, the storage and the controller has been carried out. The yearly energy gain was predicted using a validated simulation model. In addition each systems was installed as a whole and tested according the DST method, so that a direct comparison is possible.

Figure 3 shows the test results for these eleven systems according the DST and the CTSS method.

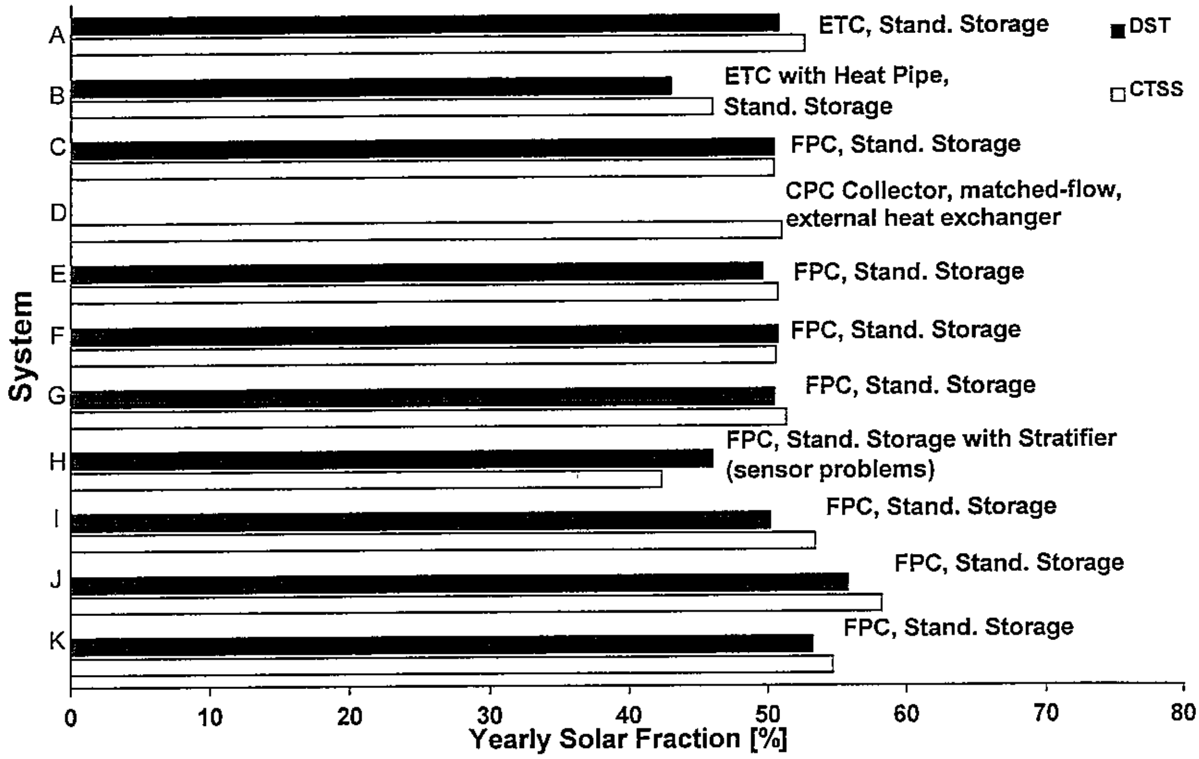


Figure 3: Comparison of the test results for eleven solar heating systems according to the DST and the CTSS method

In general the test results show a very good agreement. Apart from two exceptions the deviation remains below ±0.03 for the solar fraction. In /9/ the remaining deviations and the cases of system D and H are discussed in detail.

5 Conclusions and Outlook

A large part of the solar heating systems for hot water preparation or combined hot water preparation and space heating is offered as components that are chosen from an assortment and combined to the whole system. For these systems a component oriented test method, as the CTSS method, has several advantages over the whole system test methods. The CTSS method is more flexible and cheaper.

The DCST Group contributed with scientific work to the development of the CTSS method. The results from this work were:

- a method for testing stores for solar heating systems and
- a test procedure for the CTSS method.

With experimental investigations it was shown, that both the store test method as well as the whole CTSS method deliver accurate and reliable results. The results from the CTSS method are comparable with results from the DST method. On the other hand the method was only applied by two institutes and only on a limited number of possible system types.

The proposals of the DCST Group were already adopted by the committees of ISO and CEN for the development of an international standard for the CTSS method. For the further development of the CTSS method and the support of the standardisation work of ISO and CEN following future activities are recommended:

- Further development of the store test methods with respect to other store designs than treated within the work of the DCST group.
- A refinement of the proposed test procedure for the CTSS method towards a more strict guideline.
- An extension of the scope of the CTSS method to other system designs than treated within the work of the DCST group.
- An extensive treatment of solar heating systems for combined domestic hot water preparation and space heating.

A perspective for future scientific work is given by the promising results obtained from combined whole system and component tests.

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In Situ Testing of Solar Heating Systems - Summary by Per Isakson

1. Introduction

In situ tests of the thermal performance of large solar heating plants are required for commissioning of new plants and continuous monitoring of plants in operation. No normative test is available. However, within recent activities of the CEN technical CEN TC 312 a standard for a short-term *in situ* test is drafted. Dynamic testing opens possibilities to devise powerful *in situ* tests of the thermal performance of solar heating systems.

Figure 1 outlines the data flow of the proposed *in situ* test. The main result of the test is a prediction of the annual solar energy utilised under reference conditions defined by a Test Reference Year (TRY) and a load profile. The test is based on parameterized component models, which are derive from physical insight. The component models are integrated into a system model using a modular simulation program, e.g. TRNSYS. The test comprises the following steps:

- Sequences of **measured data** from components and subsystems are acquired during regular operation.
- The component models are **calibrated** by fitting the models to data sequences. This step produces **fitted parameter values.**
- The component models together with the estimated parameter values are combined to a **system model.**
- A comparison between the simulated and the measured energy gain (and possibly other quantities) **validates** the system model.
- The **yearly energy gain** under reference conditions is **predicted** using the system model, a test reference year, and a specific load profile.

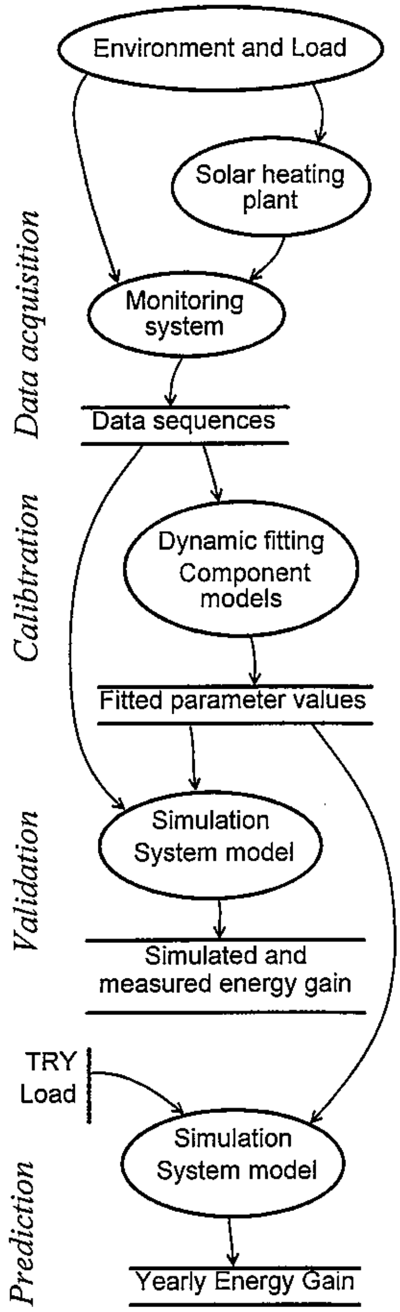

Figure 1 Data flow of the in situ test. The predicted yearly energy gain is the bottom line of the test.

1.1 Requirement analysis

The test should fulfil requirements concerning cost, accuracy, ease of use, and the maximum period of time needed for monitoring. The *in situ* test will theoretically yield a very accurate prediction of the yearly energy gain given that

- The plant encounters a wide enough range of operation conditions during the test.
- The parameterized model together with an appropriate set of parameter values faithfully models the thermal behaviour of the plant for all operation conditions.
- The monitoring system is accurate enough and data is sampled and recorded for all relevant quantities at a high frequency.

However, in practice these three items can seldom be fulfilled mainly because of the requirements regarding the cost.

- In large plants it is often both costly and difficult to perform specially designed experiments. Thus, it would be advantageous to base the test on data from regular operation. Furthermore, only with a good enough model the accuracy of the long term prediction would benefit from including non-typical operation conditions in the test.
- Accurate measurements during regular operation of large solar heating plants are expensive.
- The test must be based on generic component models, i.e. parameterized models that can be applied to fairly large classes of components. The cost among other reasons makes detailed dedicated models impossible. Furthermore, to be meaningful detailed models require extensive and thus expensive measuring programmes.

Many sources contribute to the inaccuracy of the predicted yearly energy gain:

- The model error of the system model, which comprise the model errors of the calibrated component models, the model errors of other components, and model errors due to simplified modelling of the inter-connection of the components. The errors of the calibrated models are limited as long as the operation conditions do not deviate from those of their calibration.
- The errors in the estimated parameter values, which include contributions from errors in the measured data, lack of variation in the operation conditions of the calibration period, and the fitting method itself. Furthermore, the characteristics of components might change during the calibration period.
- "Errors" in the test reference year (TRY), and the load profile used in the prediction may both strongly affects the value of the to the predicted yearly energy gain. However, these two do not contribute to the inaccuracy of the test since they are given beforehand.

1.2 Goal

The objective put up for this work is modest. It reads: Apply and further develop the dynamic testing methodology to test large SHW systems. It is supposed to deliver: Recommendations regarding experimental design, data analysis, modular simulation and validation of system models.

2. Contributions

The following countries participated in this work: Denmark, Germany, Slovenia, Spain, Sweden, and Switzerland.

2.1 In situ check of collector array performance

Miroslav Bosanac and Jan Eric Nielsen, Denmark, studied the possibility to perform a short-term collector test attaining acceptable accuracy and repeatable results (see appendix XX). They acquired accurate one-minute data during a six month period from a 60 m^2 collector array in regular operation. The measurements included the basic quantities, diffuse irradiance, and wind velocity. The collector array was connected to a domestic hot water system and thus a fair variation was obtain in the collector working temperature. There was no internal shading in the array(?).

They fitted an extended version of the dynamic collector model DynColl to data sequences from twelve selected periods each of five days. Next they made twelve predictions of the energy gain for the six month period excluding the five day period used for fitting(?). These predictions did all agree within ±5% with the measured values, respectively(?).

2.2 Development of *in situ* test procedures for SDHW systems

At ZAE, Germany, one applied *in situ* dynamic testing to eight SDHW systems during the last three year period. The area of the collector ranges from 3 to 64 m^2 and the storage volume from 0.27 to 3.5 m^3. Accurate data were recorded at a high frequency for periods of one to three years. However, diffuse irradiance is not measured.

In one of those eight cases Justus Spehr evaluated a solar domestic hot water system comprising a 7.1 m^2 collector and a 0.50 m^3 storage. The collector output and the average efficiency were 258 $kWh/m^2.a$, and 23%, respectively. The solar fraction of the yearly load was 59%. Especially in the summer the store reached high temperature values. He fitted an extended version of the DynColl(?) collector model to twenty monthly sequences of data and predicted the collector output of the year 1994. The predictions agree within ±3% with the measured value and the residuals do not depend on the season. Furthermore, he made a system model (TRNSYS) and simulated the performance of the entire system during the year 1994. The agreements with measured values are excellent for a number of quantities including the solar fraction.

2.3 Development of the ISFH - I/O - Procedure and Test in the Project Solar District Heating Göttingen

2.4 Dynamic in situ testing of a large solar system

Ciril Arkar et.al., Slovenia, evaluated a nine years old SDHW system, which includes a 57 m^2 collector and two 1.5 m^3 storage tanks. They applied dynamic system testing. The P-model. They acquired 10-minute data and half-minute data during draw-off.

2.5 Towards a performance test for large collector arrays

Per Isakson, Sweden, applied dynamic fitting to three years of available hourly data from a 5500 m^2 collector array in regular operation. The array is part of a central solar district heating plant, which also includes a 1100 m^3 storage, and conventional boilers. Internal shading occurs in the array. The yearly solar energy gain, the average collector efficiency, and the solar fraction are 2.82 GJ/m^2, 26%, and 6%, respectively. The monthly solar fraction exhibits its largest value 61% in July 1991.

The experiment was not design for dynamic fitting and thus the data exhibit some drawbacks. The diffuse irradiance was not measured. The global irradiance and the ambient temperature were measured at the plant half a kilometre off the array. The variation in the collector inlet temperature is small and the correlation between the measured quantities is large.

He fitted his MFCA model with one free parameter π^* (a linear combination of the zero loss efficiency and the collector U-value) to each of 23 monthly sequences of hourly data yielding 23 estimated values. Next for each of this values he predicted the energy collected during the 23 months. He repeated this for some variants of the MFCA model.

With the best model a third of the predicted values was within ±1% of the measured value, two thirds within ±3%, and all within ±6%. However, in this case the values of the collector parameters did take unreasonable values. Furthermore, there was a seasonal effect. The estimated values π^* of spring and autumn are larger than those of the summer.

2.6 In Situ Dynamic System Test applied to a Large Solar Domestic Hot Water System

Daniel Cabrera and Bernard Lachal, Switzerland, applied dynamic testing to a large solar domestic hot water system, comprising 200 m^2 of collector and 4 m^3 storage. It serves 126 apartments. The collectors are mounted in four rows on a flat roof and thus some internal shading occurs. The total fluid volume of the collector loop is 1.6 m^3, a third of which is in the collectors. The hydraulic residence time of the entire loop is 10 minutes.

They acquired 6-minute data during the period September 1992 through August 1993. The quality of their data is high. The collector output and the average efficiency were 430 kWh/m^2, and 36%, respectively. The solar fraction of the yearly load was 27%.

They fitted a SDHW system model (P-model, Spirkl XX) to data sequences of each month resulting in twelve sets of parameter values. Then, they used these sets to predict the solar energy gain for the total period. The predicted values agreed to measured value within ±7%. Their predictions exhibit a seasonal effect, the models fitted to the data of December and July yield the lowest predictions, and Mars and September the highest.

3. Discussion and Conclusions

Our studies indicate that the *in situ* test outlined in Figure 1 is feasible. We have not encountered any major obstacles, that would hinder the development of such an *in situ* test. Moreover, we have not encountered any problem that might increase the cost to apply the test in practice. The promising results obtained both with system and component oriented dynamic tests support our conclusion (see DST and CTSS). However, only one participant have completed a study according to Figure 1. In this single case the agreement between the predicted and the measured yearly solar energy gain was excellent. A total inaccuray better than ±6% in the predicted yearly solar energy gain appears to be possible at least in favourable cases. Thus, further work is needed to devise a specific test procedure.

The cost of applying an *in situ* test is an important aspect, especially since it is aimed at commissioning of custom built systems. There is a trade-off between accuaray and cost that we will focus on in the following discussion.

The need for variability in the measured data is pointed out in most reports on dynamic testing so also in our contributions. Nevertheless, none of us has applied a specially designed experiment to improve the variability. A fair variability in data can be expected from SDHW systems providing a high solar fraction of heat deliverd to the load (contributions 2.1 and 2.2). On the other hand as reported in contribution 2.5 the variability may be very poor in the measured data of solar heating plants, the solar fraction of which is small. However, that contribution indicates that the lack of variability might be circumvented by an appropriate parameterisation of the model. The number of free parameters being adapted to the variability of the data. Consequently we deem that measurements during regular operation will be adequate; specially designed experiments can be avoided.

A short duration of the test is important, because of the cost, and since a prompt result of a commissioning test is desirable. In most tests we have worked with data sequences of one month, and in one case five days. The latter resulted in somewhat larger inaccuaracy. However, our studies and other studies on short-term outdoor collector tests suggests that the crusial factor rather is the blend of weather types represented in the sequence than the length.

In most of our experiments we have recorded data with a high time resolution; in the range of one to six minutes. One test (contribution 2.5) used with fair success hourly data from a large collector array. The benefit of a high time resolution will depend on the type of component, the high frequency capacity of the model, the characteristics of the driving signals, etcetera. However, we did not address the cost associated with a high recording rate.

A solar collector responds differently to beam and diffuse irradiance. Thus, to measure and model the two separately should improve the accuracy of the test. Nevertheless, contribution 2.2 that did not measure the diffuse irradiance reports a very high accuray. Estimating the fraction diffuse might be an alternative to measuring. This was done in contribution 2.5, which conclude that no appropriate regression model is available to calculate the fraction diffuse based on the global irradience in the collector plane.

Two of the contributions (2.5 and 2.6) report on a similar seasonal effect. Models fitted to summer data under-predict the yearly solar energy gain, whereas models fitted to spring and autumn data over-predict. In these two cases the collector array comprise several rows mounted on a horizontal surface. Internal shading, which occurs only in these two, does probably contribute to this seasonal effect. It is important to know the fraction diffuse to correctly calculate the shading effect. Furthermore, this problem indicates the importance of long data sequences in the assessment of *in situ* testing procedures.

4. Recommendations

We recommend that the *in situ* tests for custom build solar heating systems are developed based on the dynamic testing technique. It is appropriate that this task is tackled in cooperation by an international group. We deem the following subtasks to be appropriate:

- **Requirement analysis.** Which specific test are needed? What price is acceptable in the different situations? What accuaracy is required? What is the marginal costs for extensions of a measuring program regarding various sensors, recording frequency, length in time, etcetera. Different test might be required for small and large systems, for commissoning and performance verification on a regular basis, etcetera.
- Compilation of a common **bank of measured data sequences**, the length of which are at least several months Different tentative tests need to be assessed based on the same data sequences. Some suitable data have been aquired by participants in Task 14.
- Systematic evaluation of how **accuracy** depends on the factors that have a significant influence on the **cost** to apply the test on a routine basis.
- Devopment of a **regression model** to estimate the **fraction diffuse** irradiance based on the global irradiance in the plan of the collector.
- Devise and assess tests

Solar Domestic Hot Water System Testing - Summary

by Huib Visser

1. Introduction

Work carried out in Group II 'Solar Domestic Hot Water (SDHW) System Testing' of the Subtask on Dynamic Component and System Testing (DCST) within Task 14 of the IEA Solar Heating & Cooling Programme mainly involved determination of test conditions for dynamic testing (DST) of SDHW systems. Investigations of real and simulated test data have resulted in the description of test conditions in ISO Committee Draft 9459-5 which was forwarded by the German Standards Organization DIN to ISO members for voting as a Draft ISO Standard. Presently, the Committee Draft has been upgraded into a Draft ISO Standard. The DCST Subtask activities were a direct follow-up of the Dynamic Systems Testing Group (DSTG), a Working Group within the IEA SH&C Programme ([2]).

Determination of the ultimate test conditions described in the Draft ISO Standard embodied an iterative process, for both researchers involved in investigation of real test data and the ones working with simulated data. Both investigation processes proceeded parallel, i.e. intermediate results often lead to same conclusions, hence, strengthened the way how to continue. Intermediate results have been described in progress reports and memoranda.

2. Conditions for Dynamic Testing of Solar Domestic Hot Water Systems

In general, the test conditions for characterization of solar DHW systems consist of five different kinds of test sequences:

- sequence $S_{sol,A}$ wherein system temperature is kept low for characterization of solar collector performance at high efficiency;
- sequence $S_{sol,B}$ wherein system temperature is kept relatively high for identification of store heat losses and collector performance at low efficiency;
- sequence S_{store} in which the store can loose heat during two days without interference of solar input for identification of the overall store losses, i.e. by adding this test sequence to $S_{sol,B}$ store and collector heat losses are decoupled;

- sequence S_{aux} to identify the heat losses and volume fraction of the auxiliary-heated part of the store; temperature of the auxiliary part is kept high whereas the solar part is kept cold;

3. Investigation of Simulated Data

Investigations involved both solar pre-heat and solar plus supplementary systems. The investigation method has been presented in Figure 1, DF_P being the parameter identification version of general SDHW system model P and LTP_P the performance prediction version.

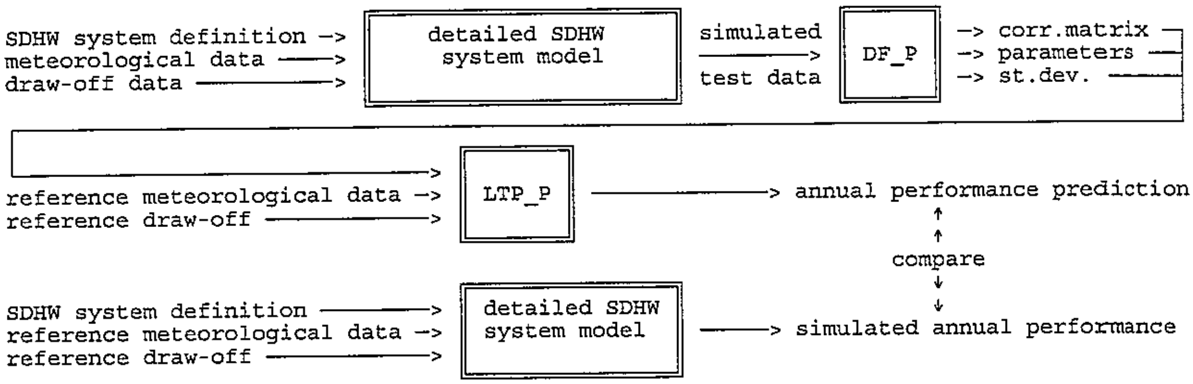

Figure 1: Scheme of the investigation method.

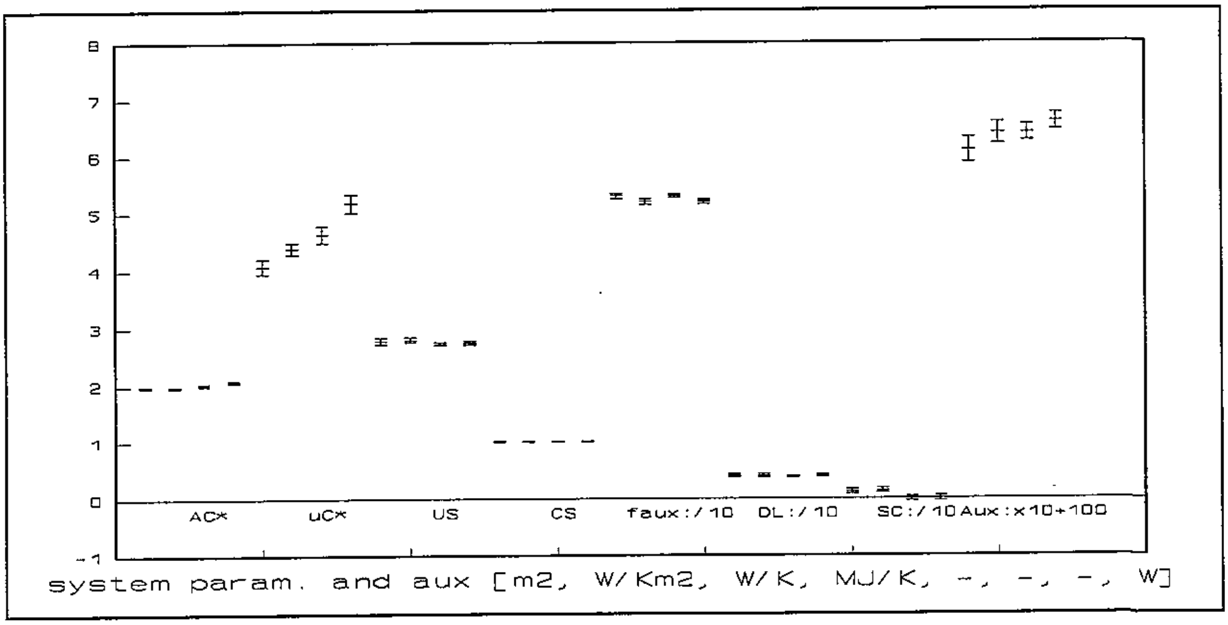

Figure 3: Results of DST parameter identification and predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, Netherlands for a solar plus supplementary system.

As an example, Figure 2 shows investigation results for a solar plus supplementary system. Different points for the parameters and performance prediction indicate different combinations of test sequences.

General conclusion is that various sets of test sequences lead to very similar parameter values. The spread in parameter values is quite small; it is relatively largest for u_C^*. It is assumed that the scatter in u_C^* cannot be reduced by improvement of the test conditions as the reason for the spread is found to be the operation of collector pump control. Moreover, the various sets of test sequences yield very comparable annual performances. The spread in annual gain and auxiliary power is minor, i.e. for various loads.

4. Investigation of Real Test Data

Experimental investigations were carried out in Germany and Switzerland.

Various tests were carried out on a German forced circulation solar plus supplementary system. Test sequences from different periods of the year were evaluated. The results show good reproducibility independent from meteorological conditions. Moreover, the standard deviations given by the data processing program turned out to be a realistic measure for the scatter of the parameter values. Scatter in A_C^* and u_C^* are largest. Also for the long term performance prediction a good agreement of the results is obtained. The scatter of the solar fraction is in the range of 2 %

Tests carried out in Switzerland showed identical results.

5. Conclusions, recommendations and follow-up

Development of test conditions has provided a test procedure from which main parameters of both solar pre-heat and solar plus supplementary systems can be determined uncorrelatedly to a large extent. This is subscribed by the results of investigation of both simulated and real test data. Various sets of test sequences within the requirements of the procedure produces very similar parameter values. Test and data processing procedure can be used for accurate annual performance predictions for very different loads and locations with very different meteorological conditions. Accuracy of annual performance prediction of tested SDHW systems is in the order of magnitude of 5 % or better. Major part of this small error is systematic, probably caused by the general character of the SDHW model in the data processing procedure.

The standard deviation appears to be a good indication for the spread in parameter values and annual performance prediction from the different sets of test sequences, i.e. if the scatter of parameters or annual performance prediction is relatively large, then, the standard deviation is relatively large.

The boundaries of the application range of the DST procedure should be investigated more profoundly. Accuracy of the method should be evaluated for systems with non-spectral selective absorbers and absorbers without cover. Systems with different flow regime in the collector loop, such as low flow and thermosyphon flow, should be taken into account as well. Finally, the procedure should be evaluated for integral collector storage systems.

These recommendations will be taken into account in a follow-up project within the EU Standards, Measurements and Testing Programme.