A SHORT TERM TEST METHOD FOR LARGE INSTALLED SOLAR THERMAL SYSTEMS

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Abstract – In order to determine the yearly energy output of solar thermal systems, we developed a quick, reliable and low-cost short term test method (ISTT-procedure), basing on the adaptation of a dynamic, component based simulation model to transient measuring data from about 6 weeks. The method is especially helpful to quickly judge the fulfilment’s of contracts concerned with guaranteed solar results (GSR). On the experimental side, an autarkic wireless measuring station for the meteorological quantities has been developed, new surface temperature sensors have been constructed and ultrasonic volume flow gauges as well as a mobile magnetic inductive volume flow station have been applied. Thus expensive wiring and cutting off the fluid circuits can be avoided. For the dynamic evaluation procedure, we tested different simulation programs using the multiport store model with four free parameters and an extended matched flow collector model with eight free parameters including pipes and a heat exchanger. Criteria for a measuring sequence sufficient for a reliable parameter identification and experimental procedures for their realization have been deduced and the parameters were numerically identified from insitu-measuring sequences not exceeding 6 weeks.

The ISTT-procedure allows to separate the influence of the operation conditions (weather and hot water demand) from the performance of the solar system. It is possible to predict the yearly solar energy gain for arbitrary standard operation conditions, especially for those supposed by the planner. In this paper, the ISTT-procedure is generally described and exemplary carried out and validated for a large solar thermal system with 110 m² flat-plate-collectors. The results of the ISTT-method excellently agree to independent long-term measurements for the energy delivered by the collector field (GSR 1) as well as for the energy discharged from the buffer store (GSR 2).

1. INTRODUCTION

We developed a reliable and inexpensive method to control the performance of large solar thermal systems after the installation. The thermal performance is commonly measured as the yearly energy output delivered by the system for standardised reference conditions. In Germany it more and more has become common, that the planner and builder of a large solar system must warrant a certain yearly energy output (ASEW, 1998), the so called guaranteed solar result (GSR). Commonly, the GSR is determined either as the amount of energy delivered from the collector loop to the buffer store (GSR 1) or as the amount of energy delivered from the buffer store to the consumer loop (GSR 2). In order to check whether the system performs as projected by the planner or builder, the actual yearly energy output $Q_{exp}$ ($Q_1$ and $Q_2$ for the actual yearly energy output after the collector loop and the buffer store, respectively) of the installed system has to be determined. $Q_{exp}$ depends on both, the performance of the system itself and the boundary conditions such as the weather and the hot water demand during the measurement. Therefore, when comparing $Q_{exp}$ to the warranted GSR, the same boundary conditions have to be used. The boundary conditions can either be the ones underlying the design of the system or the real ones measured during the operation of the installed system. So far, only the second approach is realised leading to cost intensive long term conventional monitoring over at least one year. In this approach subsequently the GSR is recalculated under the real operation conditions, and compared to $Q_{exp}$ as obtained by the long term measurement. This procedure may cause problems because neither any simulation program exactly...
fits the real system investigated nor the program is validated to the measurement. Therefore the error of such conventional procedures is commonly assessed with about 10% (ZfS, 1999). Additionally, from the juridical stand of view, the planner has only to guarantee the GSR for the conditions assumed for the planning, which value actually can be checked only by the new ISTT-procedure described below. By the conventional method it is difficult to separate the influence of the operation conditions from the system efficiency and to determine the system output for any other standard operation conditions, for example as supposed by the planner. By comparison, the yearly solar energy yield can be determined in a drastically quicker, more accurate and low-cost way, fitting a component based system simulation model to measured data over a short period (4-6 weeks) and calculating the long term energy yield with the help of the adapted simulation model for the standard operation conditions underlying the calculations of the designer. At ZAE Bayern in co-operation with the ITW of the University of Stuttgart such a short-term test procedure, the so called in-situ short term test method (ISTT-method) for large installed systems, has been developed. It promises an accuracy of better than 5% for the yearly energy output delivered under reference conditions by the collector loop (GSR1) and by the solar buffer store (GSR2), respectively. The costs nearly can be halved, compared to the long term measurement method applied so far.

2. DESCRIPTION OF THE ISTT-METHOD

The ISTT-method determines the yearly energy output of an installed solar thermal system for the boundary conditions of the design case (reference conditions) on the basis of short term measurements which are used to identify the systems performance. Since solar thermal systems show a large variety in their design, it is nearly impossible to give a detailed recipe for the treatment of each single system configuration. The ISTT-method represents more a general procedure that provides a guideline for the determination of the performance of installed systems. The ISTT-method can be subdivided into six steps which are shown in Figure 1.

2.1 Set-up of simulation model
An appropriate transient simulation program with a modular structure has to be chosen (i.e. TRNSYS, TSOL, MatLab) and the system under investigation has to be modelled.

2.2 Sensitivity analysis
A sensitivity analysis of the yearly energy output has to be carried out in order to get an impression how the output is influenced by the single component parameters.

The results of the sensitivity analysis provide an important basis for the decision which parameters have to be determined by means of parameter identification.

2.3 In-situ measurements
As the basis for the parameter identification, in-situ measurements have to be carried out over a period of 4 to 6 weeks. Details about the measuring technique and the location of the sensors see chapter 3. During the main part of this time the system is operated as usual under normal conditions. However, in order to drive the system into some extreme operation conditions needed for a reliable parameter identification, the control strategy of the system is disabled for a short period.

2.4 Determination of component parameters
In the ISTT-method, each component of the solar thermal system is described by a detailed parametric model. The set of parameter-values, which describes the thermal behaviour of the component in an optimal way is determined by means of a numerical parameter identification procedure (fit).

![Fig. 1: Structure of the ISTT-method.](image-url)
Conventional numerical fit-procedures are basing on the Levenberg-Marquardt algorithm like the commercial program package DF by insitu Software (Insitu, 1996) or Trnspid by TransSolar (TransSolar, 1997).

The reliability of the parameters and the best set of parameters are additionally determined by means of cross predictions: The total data sequence is divided into subsequences and the parameters are identified for any subsequence. Subsequently the subsequences which were not used for the parameter identification are predicted. The relative difference between prediction and measurement is an indicator for the goodness of the parameters determined, the best set identified by the lowest deviation over all subsequences. The determination and validation of the best parameter set is finished, when a certain part of the subsequences (for example 68%) can be predicted with a deviation below ±5%. In this case, the insitu-measurement can be stopped.

2.5 Validation of system simulation model
Having determined all essential parameters of the components, the next step of the ISTT-method is the numerical simulation of the thermal behaviour of the whole system. Here, it is essential that the same component models which were used for the determination of the component parameters are now used in the system simulation model. The validation of the system model is carried out in analogy to the way as described for the component models by means of cross predictions. Ideally, the model is validated at sequences containing all possible states of the system occurring under the real operation.

2.6 Prediction of yearly energy output for reference conditions
The prediction of the system performance is carried out using the validated system simulation model from the previous step. The yearly system energy output $Q_{exp}$ is calculated using the boundary conditions of the design case (reference conditions) and the parameters determined for the installed system (real parameters). A comparison of $Q_{exp}$ and the GSR (the system output predicted for the design boundary conditions and the design parameters) can be used as a basis to judge the fulfilment of contracts related to guaranteed solar results.

3. NON-INVASIVE MEASURING EQUIPMENT
To meet the requirements of a cheap, short-term and not invasive measurement, an autarkic wireless measuring station for the meteorological quantities has been developed, new surface temperature sensors have been constructed and ultrasonic volume gauges have been applied to record the mass flows in a non invasive way. The mobile meteorology station with photovoltaic power supply records the total radiation and wind speed in the collector plane as well as the ambient temperature. The station applied for a patent is mounted directly on the collector field via a acrylic-glass carrier supplied with suction-cups evacuated by a small vacuum membrane-pump, see Figure 2. By this kind of fixing, it is ready for operation within a few minutes and the cumbersome adjustment of the radiation and wind speed measuring devices can be avoided. The accuracy is the same as for conventional meteorological measuring systems with fixed installation. The weather data is collected and stored by an integrated data logger and is sent wirelessly via GSM900 mobile net to the central evaluating computer at the ZAE Bayern.

![Fig. 2: Mobile meteorological station.](image)

We developed also a new clamp-on surface temperature sensor, which consists of a steel armed Pt100 soldered in a thin silver plate. The response time of the sensor was investigated in laboratory experiments and proved to be sufficiently quick ($t_{99\%} = 10$ s and 18 s in the case of a temperature jump of 20 K for a Cu-pipe DN 20 and a steel pipe ¾", respectively) compared to conventional sensors immersed in the fluid.

To non-invasively measure the fluid volume flow rate, ultra sonic sensors have been applied, where the delay of a sound wave by the fluid motion is a measure for the flow velocity in the pipe. In the laboratory we tested the ultrasonic device of the German manufacturer Flexim, Berlin, for pipes between DN 25 and DN 40, which is typical for large solar systems and gained sufficient results for copper (accuracy 3% against magnetic inductive (MI) flow meters for volume flows rates between 750 and 2000 l/h), while for black and zinced steel the method is still not applicable (deviations up to 8%). In the solar system investigated (see also chapter 4), the volume flow rates ranged between 1000 and 1500 l/h and the ultrasonic sensors showed good agreement (1,25%) to conventional mechanical sensors of the German manufacturer Aquametro used by the ZfS, Hilden even in the case of black and zinced steel pipes. As an alternative, we developed a coupling device, which easily can be mounted in one of the dirt pans, which normally exist in large solar thermal systems. By these
devices, the fluid can be fed into a mobile MI-flow-meter to achieve highest accuracy without disturbing the normal system operation, see Figure 3a and 3b.

Fig. 3a

Fig. 3b

Fig. 3: The coupling device mounted in a conventional dirt pan (3a) with the connecting tubes and the MI-flow-meter (3b) for precisely and non invasively measuring the fluid mass flow.

4. SYSTEM INVESTIGATED

With the described experimental equipment, we carried out different periods of short term measurements at three large solar thermal systems with an collector area of more than 100 m². From the measuring data, we numerically identified the component parameters of an simulation model. With the parameters we predicted the yearly energy output of the system under different operation conditions, i.e. of the planning. Exemplary, we present the results for the large solar hot water system built up within the scope of the German BMWi-program “Solarthermie 2000” in Munich with 108 m² collector area and a buffer store with a nominal volume of 6 m³, see Figure 4.

Fig. 4: The system investigated with the measuring equipment. The demarcation line for the GSR is either the energy delivered from the collector loop to the store (GSR 1) or the energy delivered from the store to the consumer loop or load loop respectively (GSR 2).

The collector field consists of ordinary, single-glazed flat-plate collectors. The store is charged and discharged via external heat exchangers in a direct way without using any special designed stratification devices. The ratio of store volume to the collector area amounts to 56 l/m². The collector field is normally operated at relatively low temperatures (below 60 K over ambient), which can be read from Figure 7 showing half hour mean values for the total radiation in the collector plane against the collector operation temperature referred to ambient that.

The onset of the solar loop is controlled by a radiation limit (E>150 W/m²), while the pump of the store charging loop is operated depending on the temperature difference between the collector outlet and the lower part of the store (4 K onset- and 2 K offset-criterion for the design case). The system investigated showed strong oscillations in the on- and offset of the store charging pump with a period of 5 min and below.

5. REALISATION AND VALIDATION OF THE ISTT-PROCEDURE

In order to determine the collector loop parameters we carried out 2 short term measuring sequences:
- 11 days in autumn under normal operation
- 2 days in spring with strongly reduced discharging of the store leading to high collector temperatures up to 90 K over ambient.

For the store loop we measured the normal operation over ten days in spring.

For the further dynamic evaluation procedure, we modelled the system in the simulation programme Trnsys using the multiport store model (IEA, 1997) and an extended matched flow collector model (Isakson, 1995) including pipes and a heat exchanger (Spirkl et al., 1997). Subsequently, a sensitivity analysis (changing the design
values according to table 1 by 10%) was carried out yielding that the collector parameters are influencing the yearly solar output in a much stronger way than the store parameters, see Figure 5.

Following the results of the sensitivity analysis, for the store only the parameters \((UA)_{S,a}, Z_{S,in}, Z_{S,out}\) and the relative height of inlet and outlet position of the solar loop as well as \(Z_{L,in}\), the relative height of inlet position load loop have to be numerically identified. The other parameters (store volume \(V_s\), relative height of the load loop outlet \(Z_{L,out}\), vertical effective thermal conductivity in the store \(\lambda_{eff}\)) show only a small influence on the system output and have been fixed to the values as given by the producers or from test results. For the collector loop the following parameters have to be identified: the collector capacity \(C_{col}\), the optical efficiency \(\eta_0\), the coefficients describing the constant and the linearly temperature depending part of the thermal loss coefficient, \(U_1, U_2, U_p\), the loss coefficient of the pipes and the angel modifier \(f\). For the remaining parameters (as the upper dead band controlling temperature difference for the solar loop, \(\Delta T_{con}\)) the design values can be taken. Additionally the efficiency \(\varepsilon\) of the heat exchanger and the length of the pipes \(L_p\) were numerically identified from separate experiments not exceeding one day. The wind depending part of the loss coefficient has been set to zero, due to low yearly mean wind speed at the location the system is mounted. Table 1 shows the parameters identified from the insitu-measuring sequences as well as the design parameters, on which the sensitivity analysis was based.

With the insitu-parameters identified from the short term measuring sequence, the energy delivered from the collector loop to the buffer store (GSR 1) as well the energy delivered from the buffer store to the load (GSR 2) was predicted in 5 min-steps for the real operation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>((UA))</th>
<th>(Z_{S,i})</th>
<th>(Z_{S,o})</th>
<th>(Z_{L,i})</th>
<th>(\eta_0)</th>
<th>(U_1)</th>
<th>(U_2)</th>
<th>(f)</th>
<th>(C_{col})</th>
<th>(L_p)</th>
<th>(U_p)</th>
<th>(\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insitu</td>
<td>42.4</td>
<td>1.07</td>
<td>0</td>
<td>1</td>
<td>0.84</td>
<td>2.72</td>
<td>0.015</td>
<td>2.08</td>
<td>7</td>
<td>74</td>
<td>1.66</td>
<td>0.81</td>
</tr>
<tr>
<td>Planer</td>
<td>21.7</td>
<td>1.05</td>
<td>0</td>
<td>0</td>
<td>0.78</td>
<td>3.67</td>
<td>0.013</td>
<td>2.94</td>
<td>12.1</td>
<td>30</td>
<td>2.29</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 1: design- and insitu-parameters for the collector loop and the store.
conditions of the whole year 1998 as monitored by the ZfS Hilden. The calculated results were compared to the experimental solar energy output as measured by the ZfS Hilden: Fig. 6 shows the comparison for the GSR2. There is an excellent agreement for the integral value over the whole year (predicted 488 kWh/m²a, measured 492 kWh/m²a) as for the monthly values, the results for the GSR1 being similarly good.

![Energy output after the store in kWh/m²](image)

**Fig. 6:** Energy output after the store as predicted by the ISTT-method and conventionally long-term measured.

With the identified and validated parameters one can now calculate the yearly energy output also for other arbitrary operation conditions, especially for the conditions of the planning. This is possible, due to the fact, that in the ISTT-method the possible system states are widely covered during the experiments and the parameters are therefore generally valuable. The transformation to other operation conditions is the peculiar advantage of the new ISTT-method. Due to the obligation to keep the actually planning GSR-value at the secret, these results are not published in this paper.

The method also has been tested and validated for three further systems including stratified and parallel storage systems, windy locations and tube collectors. The results will be published in the final report to the project with grant number 032 97 28 A, obtainable from September 2000 at the German Federal Ministry of Economic and Technology. In this report also a description of the measuring sequences necessary for a reliable parameter determination and of the method to identify the best set of parameters is given for the collector and store loop in detail.

### 6. CONCLUSION

With the help of the validated ISTT-procedure, it is possible, in a quick, accurate and low-cost way

1. generally to predict the yearly solar output for arbitrary operation conditions (weather and load) and
2. especially to check the GSR 1 and GSR 2-values guaranteed by the planner for the standard operation conditions as used during the planning process.

### 7. OUTLOOK

In a field trial, it is planned to apply the ISTT-procedure to a set of representative large solar systems in order to achieve further experience with the ISTT-method and to further reduce the cost of the procedure to 5000-7000 Euro, which is drastically less than the long term monitoring procedures applied so far.

### ACKNOWLEDGEMENT

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