USING THE DST TEST METHOD
FOR TESTING 'SOLAR-ONLY' AND 'PREHEAT'
SOLAR DOMESTIC HOT WATER SYSTEMS

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Abstract – The European draft standard for “Factory Made” Solar Domestic Hot Water (SDHW) systems prEN 12976 (1997) [1] is entering its final phase. CEN TC 312 is likely forwarding the standard for publication within short time. With respect to performance testing, the standard refers to DST (ISO 9459-5) [2] and CSTG (ISO 9459-2) [3].
Within the EU SM&T project “Bridging the gap”[1] the DST test method has been evaluated by means of a theoretical and experimental validation programme; intercomparison tests with DST have been carried out in a number of recognised laboratories throughout Europe.
Combining the results of the calculation study and the experimental validation programme, the conclusion upon the applicability of the DST test method is:
• The DST test method will produce precise predictions of the thermal performances for ‘preheat’ and ‘solar-only’ SDHW systems, taking into consideration the aspects that define the applicability range, mentioned in [4]. This applicability holds for different testing and prediction climates, different hot water demands and for the system types common on the European market.

1. INTRODUCTION
Performance test methods for solar domestic hot water (SDHW) systems provide designers, manufacturers, installers and users with information how to represent, how to measure and how to compare the thermal performance of these systems. Suitable SDHW test methods must be able to predict a (reliable) long term (annual) performance after a (some) short term measurements in order to be broadly applicable.
The Dynamic System Test (DST) method is one of those methods. After being developed in the IEA task 3 (Solar Heating and Cooling Programme), being worked on in the Dynamic System Testing Group and in IEA task 14 (same programme), the DST method now has the status of ISO Draft International Standard (DIS) [2] and is referred to from preliminary CEN European standards [1].
Making the validation of the DST method complete, a project has been approved by the CEC Standardisation, Measurement and Testing Programme (SM&T), in order to ‘bridge the gap’ towards CEN standardisation.

It is in this SM&T project (‘Bridging the Gap’) that ten recognised laboratories throughout Europe have performed:
• simulations in order to define the scope of the DST method (Work Package 1).
• a comparison with the CSTG method; the other test method described in CEN (Work Package 2).
• experimental validation programme (Work Package 3).
This paper presents the outcome and results of ‘Using this DST test method for ‘Solar-Only’ and ‘Preheat’ Solar Domestic Hot Water Systems’.

2. DST TEST METHOD
In dynamic system testing, a mathematical SDHW model is used in order to collect as much information as possible from the available measuring data [4]. The measuring data are being obtained by a series of short outdoor tests on a SDHW system. A dynamic computer model in which this SDHW mathematical model is implemented is used for ‘parameter identification’, which characterises the SDHW system (being tested) in terms of model parameters (see table 1). In order to predict the annual thermal performance (energy saved by the SDHW system), these identified parameters and this (general) SDHW computer model are used. In figure 1 a schematic overview of the DST procedure is outlined.

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[1] Research and experimental validation on the DST performance test method for solar domestic water heaters
### Table 1: List of model parameters, characterising a SDHW system.

<table>
<thead>
<tr>
<th>symbol</th>
<th>unit</th>
<th>‘physical meaning’</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C^*$</td>
<td>m$^2$</td>
<td>Effective collector area</td>
</tr>
<tr>
<td>$u_C^*$</td>
<td>Wm$^{-2}$K$^{-1}$</td>
<td>Collector loop heat loss parameter</td>
</tr>
<tr>
<td>$u_v$</td>
<td>Jm$^{-3}$K$^{-1}$</td>
<td>Wind velocity dependency of $u_C^*$ (if applicable)</td>
</tr>
<tr>
<td>$U_S$</td>
<td>Wk$^{-1}$</td>
<td>Overall heat loss coefficient of the store</td>
</tr>
<tr>
<td>$C_S$</td>
<td>MJK$^{-1}$</td>
<td>Heat capacity of the store</td>
</tr>
<tr>
<td>$f_{aux}$</td>
<td>-</td>
<td>Auxiliary fraction of the store (if applicable)</td>
</tr>
<tr>
<td>$D_L$</td>
<td>-</td>
<td>Draw-off mixing parameter</td>
</tr>
<tr>
<td>$S_C$</td>
<td>-</td>
<td>Collector loop stratification parameter</td>
</tr>
<tr>
<td>$R_L$</td>
<td>KkW$^{-1}$</td>
<td>Thermal resistance of load side heat exchanger (if applicable)</td>
</tr>
</tbody>
</table>

One of the advantages of the method is the ‘black-box-approach’, meaning that there is no need for internal measurements or special knowledge of the system. More important, very different kinds of SDHW systems can be tested with this same method. Furthermore, the DST test results are independent on the location being tested and the performance of the SDHW system can be predicted for any climate and load profile.

Fig. 1: Schematic outline of the DST procedure on SDHW systems.

3. **WORK PACKAGE 1:**
   **DEFINITION OF THE SCOPE**

The objectives of WP1 are:
Fine-tuning of the present description of the DST procedure for predictions for different climates and hot water loads.
Clear demarcation, definition and widening of the scope of the test method, to allow for as many systems and conditions as possible.

3.1 **Overview of work done**
The most efficient way to systematically investigate the boundaries of accurate application of the DST method is to use 'Simulated Test Data' for various sites and systems. The idea is to replace the data obtained from a real DST (outdoor) test on a SDHW system by a set of simulated test data. These simulated test data are generated with a detailed simulation model of the SDHW system. The detailed model is run on real climatic data under the same conditions as they would occur in a real test, this will
generate data files that are equivalent to real measurement data files. These simulated test data files are then used as input for the DST data processing (see figure 2).

Fig. 2: Producing simulated test data

This method of investigating is a much quicker and cheaper way of producing ‘measurement data’ and many operating states of SDHW systems can be assessed and the boundaries of the scope of the DST method can be defined clearer.

3.2 Calculations
The three participants in WP 1, TNO (Netherlands), DTI (Denmark) and ITW (Germany) and the fourth voluntary partner INFA-Solar (Germany), have investigated the boundaries and limits of the DST test method [5].

With the ‘simulated test data approach’, the precision of the DST method was verified in an absolute way. The following issues have been investigated:

- SDHW system type;
  - Forced circulation systems, thermosyphon systems or ICS system
  - High flow or low-flow systems
- Collector type
  - Flat-plate black, flat-plate spectral selective - or evacuated tube collectors with two-phase heat transfer
  - Incident angle dependency of the collector efficiency
- Store influences
  - Vertical heat conductivity in ‘horizontal’ store
  - Worst-case analysis: strongly non-linear heat losses of the collector and low store temperatures during $S_{sol,b}$ sequence
- Climate
  - Testing climate
    - (i.e. Stockholm - northern climate,
    - Brussels (Uccle) - central/marine climate,
    - Davos - mountain climate,
    - Athens - mediterranean climate)
  - Climate for performance prediction
  - Testing season
    - (winter, spring, summer, autumn)
- Hot water load
- Wind dependency
- The influence of the auxiliary heater set temperature
- Error analysis: influence of systematical errors on sensors used for DST measurements
- Extrapolations of the DST result into performance predictions of identical but differently sized systems

4. WORK PACKAGE 2: COMPARISON WITH CSTG METHOD

The objectives of WP2 are:
Comparison of the DST method with the CSTG method, which is also used in the CEN, leading to correspondence factors which enable comparison of DST results with CSTG results.

4.1 Overview of work done
The four participants INETI (Portugal), CSTB (France), NCSR (Greece) and UWCC (UK) have been carried out both DST tests as well as tests using the CSTG method on SDHW systems [6].

- INETI tested two thermosyphon systems, each with non-selective flat plate collector. During the tests fans have been used in order to take care of wind influences.
- CSTB tested one ICS system with double glazing and tubular tank (surrounded by mirrors).
- NCSR tested two forced circulation systems, one with a flat plat collector, one with an evacuated tube collector.
- UWCC tested one ICS system; only a CSTG method, both indoor and outdoor.

TNO has carried out simulations according to the ‘simulated test data approach’. The data analysis has been carried out by TNO and INETI.

4.2 Results of Work Package 2
The comparison of the DST test method with the CSTG test method, which has been a separate part of this SM&T project, is discussed in a separate paper [7].
5. WORK PACKAGE 3: EXPERIMENTAL VALIDATION

Within the SM&T project, the WP3 objectives are:

- To validate experimentally the accuracy in thermal performances and application range of the DST test method specified in ISO 9459-5 [2].
- To verify experimentally the findings and recommendations established in the calculation study (WP1).
- To gain experience with the values and interpretation of the DST parameters.
- To discover possible ambiguities, omissions in the text of in ISO 9459-5 that may lead to misinterpretation and erroneous results. Formulate additions or changes to prevent these ambiguities and omissions.
- To establish the reproducibility of the DST test on solar (mechanical) systems, that have been sent all over Europe.
- To create more confidence in the DST test method by performing DST tests in many laboratories in many countries giving all labs the chance to gain experience in DST testing.

![Fig. 5: WP3 test on an forced circulation system with an evacuated tubes collector](image)

5.1 Overview of work done

Concerning ‘preheat’ and ‘solar-only’ systems, the participants of WP3 have carried out DST tests on the below mentioned systems.

- INETI (Portugal): Two thermosyphon systems
- NCSR (Greece): One thermosyphon system
- SPF (Switzerland): Two ICS systems
- DTI (Denmark): One ICS system
- FGH (Germany): One thermosyphon system.
- SP (Sweden): One thermosyphon system
- ITW (Germany): Three thermosyphon systems
- TNO (Netherlands): Two thermosyphon systems
- One forced circulation system

The results of this experimental validation programme has been reported in the Final Report of Work Package 3 [8].

6. CONCLUSIONS

This project ‘Bridging the Gap’ has led to a considerable extension of the understanding of the DST test method. The summarise conclusions of the SM&T project concerning ‘solar-only’ and ‘preheat’ systems are:

6.1 Applicability of the DST test method

Combining the results of the calculation study (WP1) and the experimental validation programme (WP3), the conclusion upon the applicability of the DST test method is:

- The DST test method will produce precise predictions of the thermal performances of ‘preheat’ and ‘solar-only’ SDHW systems (±5% - Solar Fraction or ±3% - Load), taking into consideration the aspects that define the applicability range (§6.3).
- For more critical cases the precision of the DST test method can lead up to ±10% (Solar Fraction or ±5% - Load). This applicability holds for different testing and prediction climates, different hot water demands and for the system types common on the European market.

Critical aspects concerning DST have been isolated and analysed which has led to several conclusions and recommendations described in §6.3 and §7.1.

6.2 Comparison of the DST and CSTG test method

The comparison of the DST test method with the CSTG test method, which has be a separate part of this SM&T project, is discussed in WP2-report [6] and a separate paper [7].

6.3 Conclusions on particular aspects within the DST test method

Several aspects of the DST test method have been investigated in order to define the range in which the DST test method can be used accurately. Based upon all these investigated issues, the following conclusions can be drawn:

Low-flow systems

Simulated tests on (extreme) low-flow systems showed that the DST test method is very suitable to obtain a performance prediction for these systems, especially

\[\pm 3\% \text{ - Load means that the uncertainty is 3\% with respect to the hot water load}\]
when the solar heat exchanger or manifold is extended over the total length of the store.

**Sensitivity to extrapolations**
Thermal performance predictions for other climates than the test climate lead to reliable prediction results. Extrapolations of the (design load) heat demand, ranging from 50% up to 200%, sometimes lead to increasing errors. However, these errors stay within ±10% (Solar Fraction) at the 95% confidence limits.

**Sensitivity with respect to sensor errors**
It has been extensively investigated how sensor errors would affect the DST results. The DST method is insensitive to random errors in the sensor readings. DST is sensitive to systematic errors in sensor readings. It appears that the systematic errors allowed in the ISO 9459-5 [2] still can lead to deviations up to ±5-6 % (Solar Fraction) at 95% confidence limits.

**DST parameters**
In general the parameters identified from a DST test characterises a SDHW system. However, this does not necessarily mean that from two DST tests performed the same individual parameter set result. Often it shows that (some) parameters reveal a good correspondence, some parameters reveal a cross correlation or sometimes even a poor correspondence. From all identified parameter sets and the comparison of these sets the following conclusions can be drawn:
- The $C_S$-parameter is a very constant and reliable parameter indicating the storage capacity of the storage tank.
- In many systems, both $S_C$ and $D_L$ parameters are small or statistically insignificant. In case a parameter is not significant in the parameter set identifying the SDHW system, a parameter set without this parameter can be identified and can be used for long term performance predictions as omitting this parameter(s) has no significant influence on the final prediction result.
- The parameter identification of a DST test on an ICS system, fixing the collector heat loss parameter ($u_C$) at zero shows promising results in performance predictions. This fact suggests that fixing the $u_C$-parameter at zero should be recommended for all integrated collector storage (ICS) systems.
- A separate $U_S$ determination (for an ICS) in order to obtain a physically more reasonable $U_S$-parameter value and preventing the $u_C$- and $U_S$-parameters from being correlated did not result in a realistic prediction result. The predicted output is far from the observed thermal output.

**Incident Angle Modifier**
The effect of the Incident Angle Dependency is not taken into account by the DST method. One way to express the Incident Angle Modifier (IAM) is the Ambrosetti equation:

$$ K_{beam}^{(ta)} = 1 - \tan^{1/2} (\frac{\phi}{2}) $$

With respect to the Incident Angle Modifier, one can conclude:
- Simulations show that performing a DST test on a SDHW system with an incident angle dependency comparable to $r < 0.4$ using the Ambrosetti equation, the resulting errors are insignificant.
- The DST test method gives systematic errors testing SDHW systems with a strong IAM (comparable to $r > 0.4$ using the Ambrosetti equation). However, in case the solar irradiation is adjusted for the Incident Angle Dependency, these systematic errors disappear completely (see also the recommendation in §7.2).

**Overheating during testing**
When the overheating protection mechanisms of a SDHW system are activated during the test, the precision of the test will be destroyed.

**Reverse Flow**
When a significant reverse flow (= a heat flow from the hot store to the top of the collectors) is present during nights, an uncontrolled heat loss is the result. The DST method is not able to deal with reverse flow; this will result in a performance prediction that cannot be trusted.

**Wind dependency of heat losses**
The heat losses of a collector depend on the air velocity around the collector. In case the wind dependency is not taken into account, DST identifies a mean value of the $u_C$-parameter.

For strongly wind dependent collectors this could lead to underpredictions.

For strongly wind dependent collectors, the $W_{fit}$ option (fitting of the collector wind dependency) or the $W_{force}$ option (forcing a certain wind speed over the collector during testing, using fans) of DST must be used.

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3 This applies not only to the DST method but also to similar methods that use short-time measurements to predict yearly energy gain: ISO 9459 Part 2 and ISO 9459-3.

4 Note that the $W_{fit}$ option will require longer testing before enough data is available to be able to fit the wind dependency.
**External load side heat exchanger**

A SDHW system with a load side heat exchanger in combination with the temperature dependent pump control on the (load side) pump, will not allow DST to produce a realistic prediction result.

**Component Testing**

On some of the SDHW systems a Component Test (CTSS-method) has been carried out. These investigation showed a very promising agreement in thermal performance between this Component Test method (CTSS) and the DST test method.

### 7. RECOMMENDATIONS

From this SM&T project ‘Bridging the Gap’ recommendations for CEN/TC 312 as well as recommendations for further (additional) research can be formulated.

#### 7.1 Recommendations for CEN/TC 312

**Negative system outputs**

In the ISO 9459-5 [2], it is said that during performance prediction any negative system output (cooling instead of heating of the water) is to be ignored. However for systems where the store is located outdoors, cold winter nights will allow the store temperature to decrease, the result of a negative system output. Therefore it is recommended that these negative outputs are not ignored and that the standard text is changed to reflect this.

**Overheating during testing**

When the overheating protection mechanisms of a SDHW system are activated during the test, the precision of the test will be destroyed. This must be avoided. It is recommended to add the following requirement to the ISO 9459-5:

‘When overheating occurs during $S_{sol,b}$ days, the $S_{sol,b}$ sequence should be repeated with a lower threshold temperature.’

**Sensitivity with respect to sensor errors**

DST is sensitive to systematic errors in sensor readings. It is recommended that the allowed systematic sensor deviations should be reviewed in order to see if these could be formulated more strictly.

**Changing the 12 MJ/day requirement for ‘valid’ test days**

In case a SDHW system with high heat losses is being tested within a $S_{sol,b}$ test sequence in which the daily solar irradiation barely exceeds the 12 MJ/m², the threshold temperature (defined in/for this sequence) may not be reached. This may lead to insufficient variability in the test data and thus to insufficient precision in the prediction results. In order to prevent these high uncertainties, the following extra requirement is recommended:

‘If the temperature of the water withdrawn in a $S_{sol,b}$ sequence is always below a threshold temperature, the sequence shall be extended until two consecutive days with higher irradiation (for instance 15 MJ/m²) are included’.

**Note:**

This will only occur occasionally, so the normal testing duration will not be affected.

**Reverse Flow**

The DST method is not able to deal with reverse flow. It is therefore strongly recommended to prevent this effect by carrying out a separate check for this kind of malfunctioning on each SDHW system. In case a method for checking on reverse flow does not exist, it is recommended to develop this method.

**External load side heat exchanger**

A SDHW system with a load side heat exchanger in combination with the temperature dependent pump control on the (load side) pump, will not allow DST to produce a realistic prediction result. It is therefore recommended to exclude SDHW systems with an external load side heat exchanger in combination with a temperature dependent pump control from the scope of ISO 9459-5 until sufficient experience is available for this system type.

**Wind dependency**

With respect to the treatment of the air velocity (wind) surrounding the collector, it is recommended to use the option $W_{force}$ (of the DST software) for SDHW systems with glazed collectors.

**Cold ambient test circumstances**

A DST test performed during very cold (test) circumstances ($T_{ambient} \leq 0^\circ C$) will influence the prediction results and may result in a higher prediction error. It is therefore recommended that for SDHW systems, a lower temperature limit (e.g. $0^\circ C$) is required on the average outdoor temperature during testing.

#### 7.2 Recommendations for further research

**Incident Angle Dependency**

In case the solar energy absorbed has a greater incidence angle dependency than ‘$r = 0.4$’ (in the Ambrosetti-
There can be a complication for the applicability of the DST (and also CSTG) method. A consideration of the incident angle dependency can improve the precision of the DST-method in general and extend the scope of the DST method. It is recommended that the procedure how to modify the solar radiation data should be described in more detail. Furthermore the option of radiation modification is recommended to be included in the processing software. More work will be required (exceeding the scope of this SM&T project) to include the incident angle dependency into the DST-method.

**Overheating during testing**
If the temperature enabling the overheating protection mechanisms differs too much from the overheating protection temperature in DST-LTPP (≈100°C), the thermal performance prediction will possibly exceed the limits of precision (reported in §6.1). It is recommended to have this aspect investigated.

**Extrapolation**
Preliminary simulation results show extrapolation to systems with slightly different sizes is possible using the DST method. More work will be required for systematic validation.

**Reducing DST parameters**
Some Solar Domestic Hot Water systems lead to parameter values which are either negligible, e.g. $S_C=0$, $D_L=0$, or highly cross-correlated, e.g. $u_C$ with $U_S$. Procedures are being developed to reduce the number of parameters by deriving suitable simplified models. More work is needed to show whether a general simpler model is possible.

**Weighted Least Squares Regression / Figure of Merit**
As an improvement for the DST model, the participant UWCC has introduced the principle of weighted least-squares regression (WLSR) into the SM&T-DST project team. The DST test method uses a more complicated and non-linear model. It is proposed/recommended to use WLSR with the DST model, whereby the sum of the weighted squared deviations become the so called ‘Figure of Merit’.

This ‘Figure of Merit’ could give useful information on the quality of test sequences, and thus serve as a way to optimise the sequences for speed and quality. In order to accomplish this, extra work is needed.

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**Parasitic energy consumption**
The objective of the DST test method is to be able to predict the thermal performance of SDHW systems. Reaching this thermal performance, some systems (e.g. forced circulation systems) will use parasitic energy. Research will be necessary to develop a method for the prediction of the yearly parasitic energy consumption for these kind of systems.

8. **REFERENCES**


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A rough picture of a ‘Figure of Merit’ can be the ‘Objective’ value; one can notice that in all cases, where a high ‘Objective’ value (>25W) has been observed, the specific DST test was highly suspect.