

Factory Made Solar Thermal Systems - Dynamic System Testing and development of parameter identification tool and LTPP validation.

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Abstract

This paper presents first results of a project that aims at the development of new mathematical models for characterization of Solar Thermal Systems (Factory Made Systems as defined in EN 12976) that can be used in association with dynamic system testing (non intrusive test method defined in the document ISO 9459-5) and which, based on the characteristic parameters defined in the adopted models, allow determination of those parameters by fitting between real test sequences and test sequences produced by the developed models, using fitting techniques independent of the models chosen for system characterization.

Another important goal of the project is the validation of results for Long Term (thermal) Performance (LTP) of the solar systems, based on the models developed, by comparison with long term measurement sequences obtained by the monitoring of different system types. Installation of the testing facility for this purpose is also described in the present paper.

Keywords: Factory Made systems, dynamic system test, parameter identification, Levenberg Marquardt Method, Long Term (thermal) Performance (LTP)

1. Introduction

According to EN 12976, Factory Made Systems must to be tested for determination of thermal performance, i.e, thermal energy yield, in given reference conditions [1, 2]. Presently, the European Standard EN 12976 considers two test methodologies for assessment of system thermal performance evaluation. They are commonly designated as CSTG test method and DST test method. The two test methods are part of an International Standard: ISO 9459, part 2 [3] and part 5 [4], respectively. The short designation of these test methods stands for:

CSTG – Collector and System Testing Group, which was the designation of the development group of this standard in the middle 80's [5].

DST – Dynamic System Testing, a testing methodology, first developed in the frame of IEA and its Implementing Agreement “Solar Heating and Cooling” and more specifically in Task 14 [6].

DST test method is based on the assumption of a simplified physical and mathematical model of the solar thermal system. The basic description of this physical model can be found in reference [7]. The author of the above referred article produced also a software, called DST [8] presently used by all test

laboratories that test Factory Made Systems according to the DST test method. But the DST test method is blocked by the use of closed source programme, which thus not allow for the understanding of strange results. A first attempt to reproduce the results of DST program by constructing a new software showed difficulties, taking into account that the available references are not detailed enough for this. Another attempt was to construct a new mathematical model and new software for identification of the characteristic parameters [11]. Although some results were achieved, a completely satisfactory result was not yet possible.

The present project aims at the development of new mathematical models for characterization of Solar Thermal Systems (Factory Made Systems as defined in EN 12976) that can be used in association dynamic system testing (non intrusive test method defined in ISO 9459-5) and which, based on the characteristic parameters defined in the adopted models, allow determination of those parameters by fitting between real test sequences and test sequences produced by the developed models, using fitting techniques independent of the models chosen for system characterization.

Another important goal of the project is the validation of results for Long Term (thermal) Performance (LTP) of the solar systems, based on the models developed, by comparison with long term measurement sequences obtained by the monitoring of different system types.

The main activities of the project are:

- i) Development of a software tool for parameter identification, i.e., fitting process between real test sequences and simulated sequences, independent of the mathematical model of solar thermal system chosen.
- ii) System modelling, using already developed simulation programs like TRNSYS 16 [9] , either for simulation of test sequences, as well as, for Long Term (thermal) Performance (LTP) calculation of the systems tested.
- iii) System modelling using simplified mathematical models of solar thermal systems that can cover different system types.
- iv) Monitoring of solar thermal systems, for generation of long term measurement sequences for validation of LTP calculation based on the methodologies developed in i), ii) and iii).

This paper describes the results obtained for step i) where the identification of parameters was based on an iterative optimization process using the Levenberg-Marquardt method. The paper also describes the installation of the testing facility for completion of step iv).

2. Software tool for Parameter Identification

In the test of Solar Thermal Systems the procedure for parameter identification is achieved by the comparison of the measured test sequences with simulated test sequences. These simulated test sequences can be generated by different physical and mathematical models of the solar thermal system and different simulation tools exist that can be used to generate the simulated test sequences (e.g. TRNSYS16 [9]).

Taking this into consideration, it is the objective of the present work to produce a software tool with an optimization methodology for identification of parameters that can be used with different simulation tools.

In order to develop this software tool able to perform the parameter identification of solar thermal systems, when tested according to the standards EN 12796-2 and ISO 9459-5, the Levenberg-Marquardt method was adopted [10]. The software tool was implemented in Visual Basic language.

For validation of the software tool, a first attempt was made linking it to the DST program [8] in order to generate simulated test sequences by using the DST model of the solar thermal systems. These sequences were continuously compared with real test sequences until the fulfilment of defined stop criteria of the optimization method. This procedure was applied to two different systems and the results obtained are shown in section 3.

2.1 Optimization process. Levenberg-Marquardt method

Levenberg-Marquardt Method [10] is applicable to non-linear functions in order to achieve a minimum value of the Merit Function χ^2 , which in this case is defined by the expression:

$$\chi^2(\mathbf{a}_k) = \sum_{i=1}^N [P_{Load,exp}(i) - P_{Load,model}(i, \mathbf{a}_k)]^2 \quad (1)$$

In this expression: N is the number of points in simulation; a_k are the set of parameters to be identified; $P_{Load,exp}$ is the measured thermal power delivered by the solar thermal system and $P_{Load,model}$ is the simulated thermal power delivered by the solar thermal system.

The parameters, in successive simulations, are determined according to the expression, adapted from reference [8]:

$$\Delta a_k = 0.02 \min(\max(|a_k|, 1), a_k^{\max} - a_k^{\min}) \quad (2)$$

The optimization process is repeated ten times. In order to avoid determination of local minima, the initial parameter values are established in a random form considering a Normal Gauss Distribution with $\sigma = 5 \times \sigma_{a_k}$.

2.2 Validation of the optimization software tool

The software tool was developed considering an optimization for a set of three common characteristic parameters: A_c^* , u_c^* , U_s , which are the effective collector area, the effective heat loss coefficient of the collector and the store heat loss coefficient, respectively.

In order to link, the optimization tool developed (identification of parameters), to the DST physical model of the solar thermal systems, the Short Term Prediction tool (*STP.exe*) that is part of the DST program [8] was used.

The optimization process requires three test sequences according ISO 9459-5 methodology, for solar only or solar pre heat systems. The sampling time during the tests follows the recommendations of the standard ISO 9459-5 but the *.DI* files used were compressed considering averages of 5 minutes during the periods without draw-off and a sampling time of 3 seconds during draw-off periods.

The files compressed correspond to .D3 files, used also for the comparison of results with DST program [8], as shown in section 3. In DST program [8] the physical model of the solar thermal system is described in a file with extension .df. For the present purpose the following conditions were imposed in .df file:

- “Model, Aux, Off”
- “Model, DrawoffMix, Off”
- “Model, SolarStratification, Off”
- “Model, WindCollector, Off”
- “FixPar, CS, xxxxx” (CS - Thermal capacity; value according to the system)

A set of initial values for the parameters A_c^* , u_c^* , U_s was considered and using *STP.exe* a simulated test sequence was generated. This test sequence is, in the optimization software tool, compared with the experimental test sequence and the value χ^2 is calculated and a new set of parameters calculated according to Levenberg-Marquard method as described in 2.1. With this new set of parameters, using *STP.exe* a new simulated test sequence is generated and the process repeated until the difference between a χ^2 value and a new χ^2 value are lower than 0.01. This process is schematically represented in Fig. 1.



Fig.1. Schematic interpretation for the optimization software tool developed.

3. Results

The above method for system characterization was applied to a thermosyphon and to a forced circulation system that were tested in the Laboratory. The system’s configuration is shown in Table 1.

Table 1. System configurations.

System type	Thermosyphon	Forced circulation
Collector Type	Flat Plate	Flat Plate
Collector aperture area (m ²)	2.37	1.97
Storage tank volume (l)	200	150

For comparison, the DST program [8], was used as usual (solar system modelling and parameter identification) for the two systems considered and the characteristic parameters determined. The same was done using the new software tool for parameter identification as described in 2. The results are shown in Table 2 and 3 and are also graphically represented in Fig.2.

Table 2. Characteristic parameters of **thermosyphon system**.

Parameters	Parameter determined with DST [8]	Standard Deviation	Parameter determined with new software tool for optimization
A_c^* [m ²]	1.30	0.04	1.22
u_c^* [Wm ⁻² K ⁻¹]	4.75	1.16	4.16
U_s [WK ⁻¹]	3.81	0.28	3.78

Table 3. Characteristic parameters of **forced circulation system**.

Parameters	Parameter determined with DST [8]	Standard Deviation	Parameter determined with new software tool for optimization
A_c^* [m ²]	1.16	0.02	1.14
u_c^* [Wm ⁻² K ⁻¹]	14.91	0.70	13.6
U_s [WK ⁻¹]	2.44	0.12	2.94

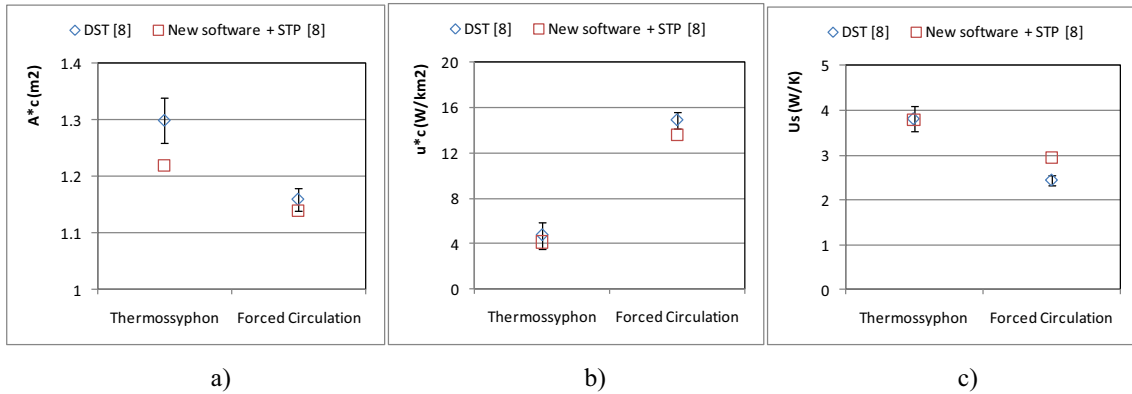


Fig. 2. Comparison of parameters A_c^* , u_c^* , U_s determined with DST program [8] and the new software tool in conjunction with DST mathematical model (STP tool [8]).

From observation of the results presented, it is possible to see that in some cases the new parameter identified has a value within the error bar of the parameter determined with DST program [8] but in some other cases this does not happen. This does not depend on system type or parameter identified.

Considering the test sequences used for parameter identification it is possible to compare the measured thermal power with the modelled thermal power with both sets of parameters. This was done considering the values simulated using the STP tool of DST program [8], using the *.DFR* file with the set of parameters generated by DST program [8] and the *.DFR* file containing the set of new parameters achieved by the new software tool for the optimization process as described in 2.. In tables 4a) and 4b) are indicated energy values (integration of thermal power values), for the 2nd day of a Type B test sequence, and for the complete test sequence, for the thermosyphon system and the forced circulation system, respectively.

Table 4a). Load Energy Values **Thermosyphon System**.

	QLoad, 2 nd day Type B Sequence [MJ]	[%]	QLoad, Total [MJ]	[%]
DST	21.75	-5.1	221.61	-14.1
<i>Software tool</i>	20.95	-9.1	185.47	-19.5
Measured	22.86	-----	170.14	---

Table 4b). Load Energy Values **Forced Circulation System**.

	QLoad, 2 nd day Type B Sequence [MJ]	[%]	QLoad, Total [MJ]	[%]
DST	42.78	4.2	142.05	-4.9
<i>Software tool</i>	42.24	2.9	138.50	-7.6
Measured	41.00	-----	149.00	-----

In general both sets of parameters underestimate the power delivered by the system tested. The parameters determined with DST Program give a better approximation to the measured values.

Since the solar systems (thermosyphon and forced circulation) were modelled using the DST Program [8], the differences of approximation are due to the method for parameter identification, which in the new software tool is Levenberg-Marquardt Method.

The power delivered by the systems, measured and calculated with the different sets of parameters is represented in Figures 3a) and 3b), only for 2nd day of a Type B test sequence, for the thermosyphon and forced circulation system, respectively.

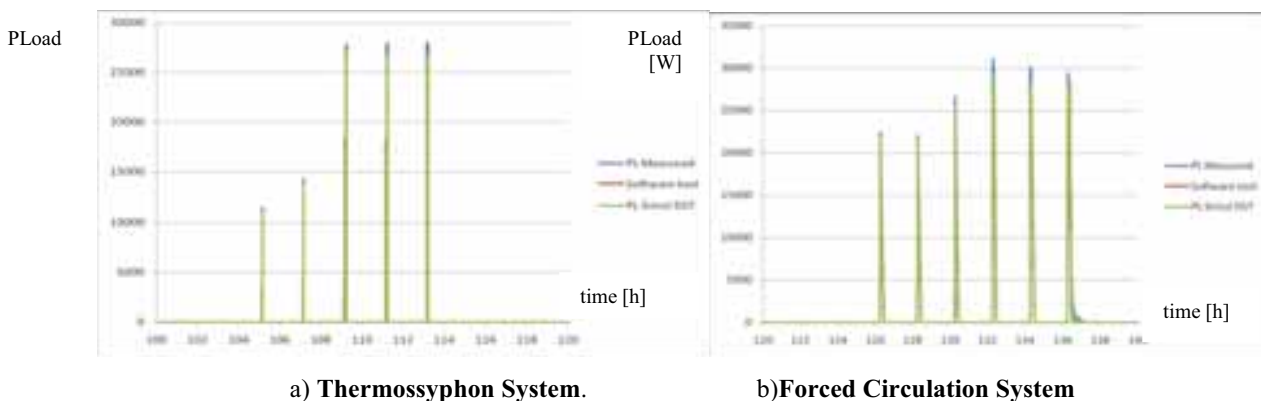


Fig. 3. Measured and Simulated thermal power (Load)

4. Validation of LTP results: monitoring of solar thermal systems and LTP calculation

As referred in the introduction, the project under way has also the objective of comparison of long term thermal performance results based on the simulation and optimization tools developed and measured LTP results. With this objective an experimental test rig was designed to test two solar systems simultaneously. In this test rig it will be possible to perform test sequences according to ISO 9459-5 and also to monitor the systems with load profiles that are equivalent to the real use and to

compare the measured energy delivered by the systems with the LTP calculations based on the simulation and optimization tools.

One of the requirements for the design of the test rig was that the temperature of water at the systems inlet is kept close to mains water temperature using as less fresh water as possible, i.e., minimizing the tap water consumption. The test rig is schematically represented in Figure 4. The tank 1 receives the hot water from the solar thermal systems, which will be drained to tank 2 by gravity the day after. In order to minimize the tap water consumption, the thermal load from the solar thermal systems will be dissipated during the night in a direct contact cooling tower coupled to tank 2 with a flat plate heat exchanger. According to the standards, the inlet water temperature in the systems, will be adjusted in a fixed value and with a specific tolerance, with a help of a 3 way motorized modulated valve.

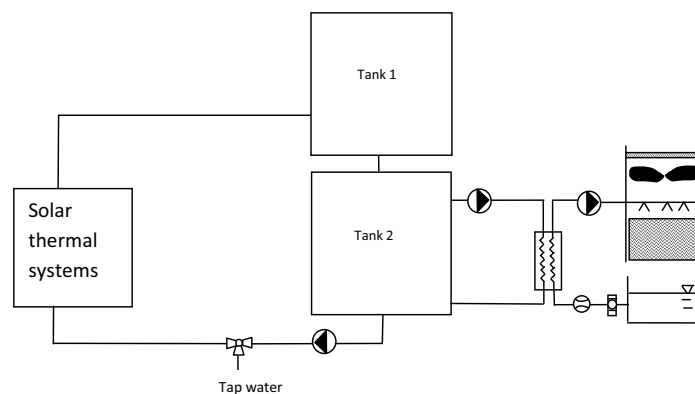


Fig. 4. Simplified layout of the experimental facility to test the solar thermal systems.

For control of the test rig (pumps and electromagnetic valves) and for monitoring of the solar thermal systems (measurement of temperature, irradiance and flow), a software is prepared that uses as control unit and data acquisition a multimeter (Keithley 2700). The sampling rate is set according to the recommendations of ISO 9459-5. It will be possible to perform test sequences according to this standard as well as ISO 9459-2.

The software is developed in Visual Basic.Net in the Visual Studio 2005 Environment, since the monitoring software tool does not require much calculation effort and the programming can be done by objects and using “multithread” capabilities. To allow user interaction while the tests are running, the program has two threads of execution: one is for the user interface; the other, running in background, controls the tests through the data acquisition system. The communication between threads is done through a reduced number of variables with protected access and by using the primitives available in the .Net Framework for inter-thread synchronization.

5. Final conclusions

In the frame of a research project, whose objective is the development of new mathematical models for characterization of Solar Thermal Systems that can be used in association with dynamic system testing (ISO 9459-5) and which, based on the characteristic parameters defined in the adopted models, allow determination of those parameters, first results are presented in what refers to the development of a software tool for parameter identification, i.e., fitting process between real test sequences and simulated sequences, independent of the mathematical model of solar thermal system chosen.

The software tool was developed for parameter identification using the Levenberg-Marquard method [10]. A very simple model for the solar thermal system was adopted with only three parameters:

A_c^* , u_c^* , Us . The results presented, show that in some cases the new parameters identified have values within the error bar of the parameter determined with DST program [8], but in some other cases this does not happen. This does not depend on system type or parameter identified. Since the solar systems (thermosyphon and forced circulation) were modelled using the DST Program [8] the differences of approximation are due to the method for parameter identification - Levenberg-Marquard Method [10].

In the analyses of the present results it should be taken into consideration that the limited application of this method just to two systems, may not be enough to conclude about the validation of this optimization process. Further research is needed in order to evaluate better if this method is the adequate for the identification of parameters needed.

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References

- [1] – EN 12976:2006, Thermal solar systems and components - Factory made Systems - Part 1: General requirements; Part 2: Test methods.
- [2] – ENV 12977-1, Thermal solar systems and components — Custom built systems — Part 1: General Requirements; Part 2: Test methods; Part 3: Performance characterization of stores for solar heating systems.
- [3] – ISO 9459-2:1995, Solar heating – Domestic water heating systems – Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems.
- [4] – ISO 9459-5, Solar heating – Domestic water heating systems – Part 5: System performance characterization by means of whole system tests and computer simulation.
- [5] – Recommendations for performance and durability tests of solar collectors and water heating systems (Part A), Aranovitch, E., Gilliaer, D., Gillet, W.B. and Bates, J.E. (Eds.),1989.
- [6] – Dynamic Testing of Active Solar Heating Systems, Final Report of the Task 14 – Dynamic Component and System Testing Subtask, IEA Solar Heating and Cooling, Huib Visser (Ed.), TNO, The Netherlands, 1997.
- [7] – Spirkel, W., Muschaweck, J. (1992), General model for testing solar domestic hot water systems, Solar Energy Materials and Solar Cells, vol.28, pages 93-102.
- [8] – Dynamic System Testing, Programme Manual, Version 2.7, In Situ Scientific Software.
- [9] – TRNSYS, A Transient System Simulation Program, 2009.
- [10] – Teukolsky, Saul A., Vetterling, William T., Flannery, Brian P., *Numerical Recipes in Fortran, The Art of Scientific Computing*, Second Edition, William H. Press, Cambridge University Press
- [11] – Neves, A., M. J. Carvalho, Modelling of Solar Thermal Systems (Factory Made Systems) and identification of the characteristic parameters for LTPP, Eurosun2006.