EVALUATION PROCEDURE FOR STORAGE TANK TESTS USING THE COMBINATION OF TRNSYS WITH GENOPT AND NEW PROPOSAL FOR HOLISTIC ERROR ESTIMATION

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1. Introduction

The Fraunhofer Institute for Solar Energy Systems (ISE) has been operating a test center for solar thermal systems since 1997. Within this test center in- and outdoor test stands are operated for performance and functional testing of solar collectors and for prefabricated solar thermal systems for hot water preparation.

Custom built solar thermal systems can have a large number of possible combinations of the various components. Therefore, it is appropriate to have component-wise performance evaluation of solar systems for domestic hot water and/or for space heating according to CEN/TS 12977-2:2010 (CTSS - component testing system simulation). According to the CTSS method controller, storage tank and collector will be tested individually. Based on the determined parameters of the components, a simulation for calculating the energy output of the whole system is performed later. In this way, a lot of different combinations can be evaluated within acceptable costs.

To test the component store, Fraunhofer ISE established a test stand and implemented an evaluation procedure with TRNSYS and GenOpt to determine the storage parameters according to EN 12977-3:2008 (domestic hot water storage tank) and CEN/TS 12977-4:2010 (combistores). With this method, parameters such as heat loss rate can be determined on basis of the measurement data (measured input and output) of the tested store. A parameter identification procedure is used to determine the parameters. The “Generic Optimization Program” GenOpt performs iterative TRNSYS (TRaNsient SYstems Simulation Program) simulations continuously adjusting parameters of the storage tank model and comparing simulated output with measured output. When the difference between measured and simulated outputs, which is calculated in a target function called “objective”, is minimized to a certain degree, the simulation represents the thermal behavior of the store with sufficient accuracy and therefore the store parameters are identified.

The considered store in the subsequent investigations is a typical solar water heater storage tank with 300 liters nominal capacity and two immersed heat exchangers.

2. Normative validation of the evaluation procedure

A parameter set determined by parameter identification can be validated according to EN 12977-3:2008 Annex B. Verification sequences which have not been used to determine the storage parameters are used for the validation. The permissible error between simulation and measurement (of power transferred through each hydraulic circuit) must be lower than 5 % (validity criterion). For the examined storage tank the error was with a maximum of 4.6 % below the validity criterion. Previously, the evaluation procedure was validated according to 12977-3:2008 Annex C. Within this evaluation procedure, parameter identification on the basis of input and output storage tank measurement data from the German Institute for Standardization was carried out and an error analog to 12977-3 Annex B was calculated. A maximum error value of 1.9% was obtained which is significantly lower than the maximum permissible error of 3%.

3. Uncertainty of storage tank parameters by evaluation procedure

When carrying out several parameter identifications with an identical measurement data set, a model with (partially) correlating parameters leads to several different parameter sets. Therefore the goal of the subsequent analysis is to determine whether these parameter sets still provide a basis for reliable system simulations according to the CTSS method. Furthermore, it should be found with what repeat accuracy the storage tank parameters can be determined.

Four sets of parameters have been identified using the Hooke Jeeves algorithm. All parameter sets satisfy the said validity criterion. It can be assumed that the statements made below are transferable for storage tanks with a similar design.

In tab. 1 for each parameter type the maximum relative deviation of the average range is specified (subsequently called "deviation"). The average range is defined as the difference between maximum and minimum value.

$$\textit{relative deviation of average range}\,[\%] = \pm\left(\frac{\textit{maximum value}}{\textit{average range}} - 1\right)\cdot 100 \qquad \text{(eq. 1)}$$

The deviations listed in tab. 1, cannot be understood as a general error indicator for the storage parameters, since they contain no error component from the data logging system. This topic is discussed separately in section 5. For some parameters with strong correlation, the deviation shown in tab. 1 is not meaningful, e.g. for the heat loss rate through the bottom $(UA)_{S,bot}$ since this parameter correlates with the heat loss rates through the storage tank side wall $(UA)_{S,wall}$ and through the top $(UA)_{S,top}$. Therefore the deviations for these parameters are much higher compared to the deviations for the other parameters. Therefore the deviations for these parameters are not given, instead the deviations for the heat loss rate and the heat transfer capacity are combined to single storage tank parameters (second column) and a deviation for these parameters are given.

The highest deviation constitutes in the number of nodes N_{nodes}. It can be used as an indicator for reduction of thermal stratification during discharge. In state of the art storage tanks usually certain design measures prevent the destruction of the thermal stratification when streams of water enter the storage tank. Such a storage tank tested will most likely have an identified number of nodes in the range of 100 or higher. Sensitivity analysis has shown that different numbers of nodes in the range of 100 to 199 have little impact on the solar fraction (less than 0.05 % difference in f_{sav}). Thus the parameter is only of minor significance.

The second biggest deviation is reflected in the "effective vertical thermal conductivity" λ_{eff}. [DRÜCK] describes λ_{eff} as a parameter of 2nd order which hardly affects the thermal behavior. A certain correlation between individual parameters of the heat loss rate and λ_{eff} is assumed as the parameter reacts sensitive to changes of individual components of the heat loss rate.

Tab. 1: Maximum relative deviation of average range (eq. 1) of storage tank parameters from a limited sample size of evaluations of a storage tank test. Some of the determined parameters are combined due to strong correlation.

Determined parameters	**Combined parameters**	**Meaning**	**Deviation of valid parameter sets [%]**
λ_{eff}	-	Effective vertical thermal conductivity	λ_{eff} ±3.0
N_{nodes}	-	Number of nodes	N_{nodes} ±6.0
$z_{hx,NK,in}$	-	Relative height of the inlet position of the auxiliary heat exchanger	$z_{hx,NK,in}$ ±1.0
V_S	-	Capacity of the entire heat storage tank	V_S ±0.2
$(UA)_{S,bot}$ $(UA)_{S,top}$ $(UA)_{S,wall}$	$(UA)_S$	Heat loss rate of the entire storage tank	$(UA)_S$ ±0.8
$K_{hx,SK}$ $b_{3,hx,SK}$	$(UA)_{hx,SK,20^\circ C}$	Heat transfer capacity of the heat exchanger in the solar loop at 20°C, 40°C, 60°C average water temperature	$(UA)_{hx,SK,20^\circ C}$ ±2.5
	$(UA)_{hx,SK,40^\circ C}$		$(UA)_{hx,SK,40^\circ C}$ ±0.5
	$(UA)_{hx,SK,60^\circ C}$		$(UA)_{hx,SK,60^\circ C}$ ±0.6
$K_{hx,NK}$ $b_{3,hx,NK}$	$(UA)_{hx,NK,20^\circ C}$	Heat transfer capacity of the heat exchanger in the auxiliary loop at 20°C, 40°C, 60°C average water temperature	$(UA)_{hx,SK,20^\circ C}$ ±2.1
	$(UA)_{hx,NK,40^\circ C}$		$(UA)_{hx,SK,40^\circ C}$ ±0.5
	$(UA)_{hx,NK,60^\circ C}$		$(UA)_{hx,SK,60^\circ C}$ ±1.2

The parameters "relative height of the inlet connection of the auxiliary heat exchanger" $z_{hx,NK,in}$, the combined "heat loss rate" $(UA)_S$, and in particular the capacity of the storage tank V_S show a small deviation. The parameter $z_{hx,NK,in}$ is needed to determine the thermal capacity of the auxiliary volume.

The combined parameters $(UA)_{hx,SK}$ and $(UA)_{hx,NK}$ describing the heat transfer capability of the heat exchanger, show partially larger deviations depending on the mean temperature level in the area of the heat exchanger. The parameter b_3 describes the dependence of the heat transfer capability on the viscosity (respectively the temperature) of the fluid. Studies showed that the parameter b_3 has a large influence on the outcome of the objective and therefore should always be identified in a parameter identification process.

The same applies to parameter b_1 if the test sequences contain variations of the mass flow rate through the heat exchanger. Parameter b_2 showed no significant impact on the objective. This parameter describes the dependence of the heat transfer capability of the temperature difference between heat exchanger inlet and the temperature of the fluid in the corresponding storage tank segment (at the height of the inlet).

The influence of different parameter sets on the fractional thermal energy savings f_{sav} of a typical solar thermal system was examined[1] in an annual simulation based on [12977-2] and compared in tab. 2.

Tab. 2: Comparison of calculated f_{sav} values based on different sets of parameters (ISE 1 to 4) in comparison to a simulated f_{sav} based on a set of parameters of an identical storage tank that was measured at the Institut für Thermodynamik und Wärmetechnik, Stuttgart (ITW).

	ISE 1	**ISE 2**	**ISE 3**	**ISE 4**	**ITW**
$\mathbf{f_{sav}}$	63.06%	62.52%	62.81%	62.72%	63.36%

According to tab. 2 the four parameter sets with its distinguishing parameters caused by correlations due to the simulation model show little impact on the fractional energy savings. The average range of the values based on the parameter sets ISE 1-4 is 62.79 % with a deviation calculated according to eq. 1 of ±0.43 %.

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[1] DHW-System, Site: Essen in Germany, Load: 175 l/d at 45°C,
auxiliary heater with set temperature = 52,5°C, A_{ap} = 7,08 m², V_{store} = 300 liter

The fractional energy savings calculated on the basis of the parameter set of an identical storage tank, measured at Institut für Thermodynamik und Wärmetechnik ITW, only differ slightly. The test procedure as well as the evaluation procedure leads, considering this limited sample size, to good matching results.

4. Algorithms in GenOpt

The software GenOpt is suitable for the evaluation procedure which is described in the present paper. GenOpt features a user-friendly interface which displays the parameter identification process graphically. Moreover GenOpt offers various algorithms. In [WEATHER, WRIGHT] these algorithms were tested with the building simulation software Energy Plus. From a numerical point of view this software is comparable with TRNSYS. Based on these studies, the most powerful algorithms for the evaluation procedure were selected and tested (tab. 3).

Tab. 3: Assessment of the tested algorithms for the evaluation procedure.

Algorithm	Advantages	Disadvantages
Particle Swarm Optimization (**PSO**, Evolutionary Algorithm)	Effective also with wide (unknown) parameter interval limits Result independently from choice of initial values	Converges usually further away from the presumed global minimum
Hooke Jeeves (**HJ**, General-Pattern-Search Algorithm)	Finds the lowest target function value (multi-start mode)	Many search runs needed, therefore parameter identification takes comparably very long (multi-start mode)
Combined algorithm: PSO-HJ	Combines meaningful advantages of PSO und HJ, therefore good results on single search run	Usually not the best result since no multi-start mode available

The lowest objective could be achieved using the Hooke Jeeves (HJ) algorithm. This algorithm however depends on good initial values meaning narrow interval limits in which the global minimum is assumed and an appropriate step size (small enough to be precise, big enough to be not too time-consuming). In multi-start mode, multiple search runs can be automatically set up and the lowest objective can be found. At the beginning of the parameter identification process the interval where the parameters are assumed can be unclear; then the interval limits have to be chosen accordingly wide. In this case PSO-HJ (combined Particle Swarm Optimization and Hooke Jeeves algorithm) can be used to approximate smaller interval limits. In a second step applying HJ algorithm will more effectively achieve low objectives.

Another finding is that parameter sets which achieve low objectives will also lead to lower errors in the verification sequences. However, also exceptions were found.

5. Method to quantify the error of the storage tank parameters

The parameters determined by parameter identification are influenced by the following sources of error [DRÜCK]:

1) Measurement errors

2) Errors caused by the simulation model

3) Errors caused by the optimization procedure

The parameters determined with the test sequences can be checked for conformity using verification sequences. This verification procedure considers errors caused by 2) and 3). Since in both cases the same data logging system is used, in both test and verification sequences, the calculated error cannot contain any information about errors caused by measurement deviations. Thus it is not suitable to make a statement about the errors of the determined storage tank parameters. The following considerations do not intend to provide a solution to investigate the influence on storage parameters of a faulty data logging system. Instead the presented proposal aims to examine the impact of the accepted measurement uncertainty given in the standard (flow rate: 2 %, etc.) on an identified set of parameters.

A calculation of the error according to GUM (Guide to the Expression of Uncertainty in Measurement) is not feasible as neither the model error nor the error caused by the optimization procedure can be estimated reasonably. However, such error models are a requirement for the application of GUM. Up to now there is no generally accepted method for the holistic error estimation of determined storage tank parameters.

Problems where an analytical solution is not possible or does not produce satisfactory results can be achieved by random experiments that are carried out very often (Law of large numbers). In this section a proposal for a single holistic error estimation method for typical domestic hot water storage tanks and combistores based on Monte Carlo experiments is presented (fig. 1).

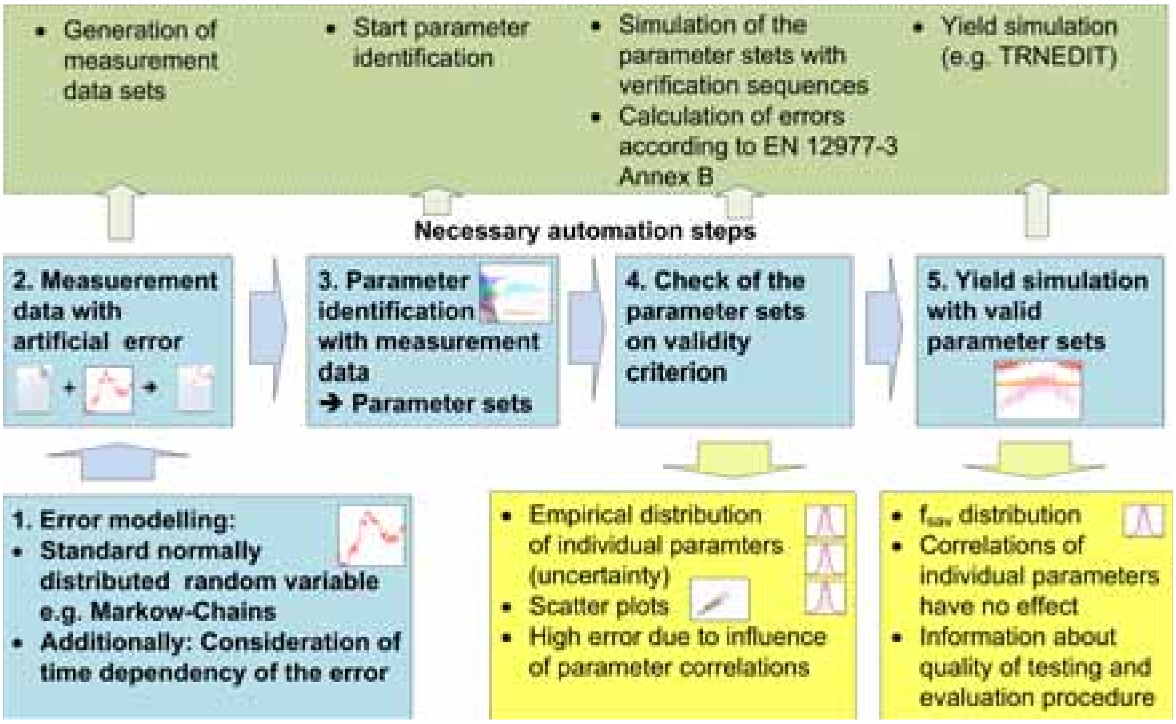

Fig. 1: Error estimation of storage tank parameters by modeling of measurement errors, multiple parameter identification and yield simulation.

The principle of the proposed method is modeling of typical measurement errors (Step 1). Afterwards different artificially modeled errors are added to measurement data from a storage tank test. Therefore many different measurement data files with artificial errors are generated (Step 2). The following steps 3 and 4 comprise the evaluation of these modified data sets and finally system simulations (Step 5). Thereby an automation mechanism is required in order to be able to carry out the necessary steps in reasonable time (Necessary automation steps). In order to provide sufficiently good results, a very large number (>1000) of parameter identifications and simulations might be necessary. The actual number of simulations cannot be predicted in advance.

In step 4 one can investigate whether or not it is useful to add the same artificial error to the verification sequences as to the test sequence. After all this step might have an effect on the amount of parameter sets that are finally included in the error estimation process. However, since additional effort is necessary, does not seem to be recommendable.

For the determined and validity checked parameter sets parameter normal distributions and therefore the wanted error limits of individual storage tank parameters can be derived. Furthermore scatterplots can be generated to visually present correlations between individual parameters. The derived error limits will be high for parameters which are correlated to a high degree with other parameters. For these parameters a statement of the grade of the evaluation procedure is limited. In order to bypass this problem yield simulations can be performed to calculate the fractional energy savings of each parameter set and therefore combine all correlated parameters. In conclusion a more meaningful error limit for the grade of the entire measurement and evaluation procedure can be stated.

As mentioned earlier the grade of the error modeling will determine the quality of the performed error estimation. In a rather simple case standard normal distributed random variables can be generated (e.g. Box Muller method) and transformed to a normally distributed measurement error. Following the central limit theorem of the probability theory a normal distribution for measurement values can be assumed, because they are usually available as arithmetic average values.

This approach assumes time independent measurement errors. Therefore the actual measurement error will clearly be overestimated because in reality there is a time dependency between consecutive measurement errors. One possibility to model such time dependencies are Markov-Chains which can also be generated using a random generator. Finally, by using the Glivenko theorem and by carrying out a sufficient number of simulations, empirical distributions which approximately correspond to the true error distribution can be obtained.

6. Conclusion

The testing of solar storage tanks according to EN 12977-3:2008 and CEN/TS 12977-4:2010 can be divided into a measurement phase at the test stand and an evaluation phase using a simulation program coupled to an optimization program to determine the characteristic values of the storage tank. This paper deals with the evaluation procedure that has been worked out at the TestLab Solar Thermal Systems of Fraunhofer ISE and validated according to the standard. Furthermore, investigations based on exemplary measurement data of a measured solar water heater storage tank have been carried out.

In the first part it is being analyzed which inaccuracy can be expected when determining the storage tank parameters. The accurately ascertainable parameters are thermal capacity of the entire storage tank, the heat loss rate and the auxiliary heated volume. Yield simulations show that differences in parameter sets which are caused by parameter correlations have little effect on the fractional energy savings.

In the second part advantages and disadvantages of different tested algorithms are compared. The Hooke Jeeves (HJ) algorithm shows best results, however carrying out evaluations using this algorithm is very time consuming. It turned out that the application of the combined Particle Swarm Optimization and Hooke Jeeves algorithm (PSO-HJ) in the beginning of the evaluation process is useful in case the parameter intervals are not clear.

The validation procedure described in EN 12977-3:2008 does not consider errors of the data logging system. Therefore in the third part a new proposal is presented how holistic error estimation based on the Monte Carlo method could be performed in order to specify the uncertainty of the determined storage tank parameters.

7. References

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