Annex xxx
General guidelines for the assessment of uncertainties in solar thermal systems performance testing

1 Introduction

The expected energy output presents the most important quantity, within those quantities used for the energy characterization of the systems utilizing renewable energy sources in general, and solar domestic hot water systems (SDHWS) more specifically. The continuously increasing penetration of energy certification schemes and the connection of the expected energy gains with supporting actions, motivated by the demand on the users part for reliable performance data of solar thermal products, makes necessary the estimation of uncertainty characterizing the test results.

The aim of this annex is to provide a general guidance for the assessment of uncertainty in the expected annual energy output of a SDHWS tested performed according to the present standard. The need for a well defined methodology for the assessment of uncertainty in system performance testing results arises due to the peculiarities of the related calculations. More specifically, the final result is not derived by a single direct measurement, but it is the outcome of the combination of a large number of primary measurements supported by intermediate calculations, on a procedure consisting of multiple stages.

This standard proposes two methods for the performance testing of SDHWS, the DST and CSTG method, on the basis of two different approaches for the modeling of the energy behaviour of the systems. It should be noted though that, as regards the estimation of uncertainties, the DST method presents some additional difficulties related to the energy model used, as this model is not exactly known and the calculations implemented by the respective software are not known to the user.

It is important to note that the proposed methodology is one amongst the possible approaches for the assessment of uncertainty; other approaches can also be implemented, given that they are compatible with the up-to-date metrological concepts for the estimation of metrological uncertainty (BIPM et al., 2008a). It lies upon each Laboratory to choose and to implement a scientifically valid approach for the determination of uncertainties, according to the recommendations of the accreditation bodies, where appropriate.

2. The testing method and the measurement model

According to the Standard, the energy behavior of a SDHWS can be sufficiently described by a specific model which relates its energy performance with a series of parameters (mainly climatic ones) influencing the operation of the device. More specifically, the estimation of the expected energy output is performed on three main stages:

- At the first stage, that of testing, specific operation scenarios are realized, aiming at the gathering of the required experimental data. These data are processed, where necessary, for the calculation of intermediate quantities which are involved in the energy model as input parameters (e.g. the incident daily solar radiation on the collectors plane for the CSTG method or the load capacitance rate through the store for the DST method).
- At the second stage, the coefficients of the characteristic equation of the system under test are determined. This equation simply represents the mathematical expression of the energy model.

- At the third stage, that of the expected energy output calculation, the energy characteristics identified through the tests are used for the calculation of the expected energy output. Calculations are performed for a specific site, where the system is expected to be installed, for conditions determined by the Typical Meteorological Year (TMY) of this area and for specific hot water use patterns.

Thus, the whole procedure involves a series of discrete calculation activities, the combination of which can be considered as the measurement model. The exploitation of the measurements data for the calculation of the expected annual energy output involves calculations on multiple steps, noting that it is not possible to formulate explicitly a measurement model for the connection of primary experimental testing data with the calculated final result. The absence of such a model leads to specific difficulties as regards the estimation of uncertainty on the final energy result, to the degree that it makes the adoption of the conventional approach for error propagation impossible. It is noted that the measurement model describes the relation of the final result to the primary experimental data, and should not be confused with the energy model which describes the energy behaviour of the system.

3. Sources of uncertainty and influence on the final result

3.1. General

The assumption that the requirements of the Standard regarding the implementation of the test method are satisfied is made. Potential deviations from the method can introduce additional uncertainty components, which should be assessed case dependently.

Thus, the calculation of the uncertainty characterizing the expected annual energy output can be implemented on five distinct steps:

I. Initially, the uncertainties related to the intermediate quantities are estimated, on the basis of the metrological characteristics of the measuring equipment.

II. The stochastic information which has been produced for the experimental values of intermediate quantities is propagated through the measurement model, aiming at the estimation of both the expectation and the variance of the calculated energy output.

III. The uncertainty component related to the imperfections of the energy model, i.e. its inability to explain precisely the experimental data gathered during the test, is estimated.

IV. The uncertainty related to the fact that the meteorological conditions which may occur during the actual operation of the SDHWS system cannot be precisely known, is estimated.

V. Finally, the combined uncertainty characterizing the final result is computed.

In the following paragraphs general guidance is provided for the practical implementation of the above mentioned steps. More detailed information for the calculation procedure can be found in the relevant literature (Mathioulakis et al., 2012; Bourges et al., 1991).

3.2. Calculation of uncertainties of intermediate quantities

The uncertainties related to the intermediate quantities are not directly known, but they can be calculated according to the metrological characteristics of the measurement devices. For the calculation of the standard uncertainty, the following general rules can be applied (BIPM et al., 2008a; Lira, 2002):

I. Standard uncertainties in experimental data are determined by taking into account Type A and Type B uncertainties. The former are the uncertainties determined by statistical means while the latter are determined by other means. Type A uncertainties account for the fluctuations in the measured value during the measurement, if any. In the case of repeated observation, the best estimate of the measurand is the arithmetic means and its Type A uncertainty is the standard deviations of the mean. In cases where no arithmetic mean of the repetitive measurements is used, as in the case of the quasi-dynamic model, Type A uncertainty component equals zero. Type B uncertainty derives from a combination of uncertainties over the whole measurement chain, taking into account all available information. Relevant information should be obtained from calibration certificates or other technical data related to the devices used.

II. The uncertainty associated with a measurement of an intermediate quantity is the quadratic sum of all Type A and Type B uncertainty components.

III. In most cases an intermediate quantity Y is determined indirectly from P other directly measured quantities $X_1, X_2,...,X_P$ through a functional relationship $Y=f(X_1, X_2, ...X_P)$. Such is the case of the thermal power drawn-off by the system. Then, the standard uncertainty in the estimate y of Y is given by the *law of error propagation,* as a function of the estimates $x_1, x_2, ...,x_P$ of $X_1, X_2,...,X_P$, taking also into account the respective standard uncertainties $u_{x1}, u_{x2}, \ldots u_{xp}$:

$$u_y = \left(\sum_{i=1}^{P} \left(\frac{\partial f}{\partial x_i} u_{xi} \right)^2 + 2 \sum_{i=1}^{P-1} \sum_{j=i+1}^{P} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \operatorname{cov}(x_i, x_j) \right)^{1/2} \tag{1}$$

In cases the estimates $x_1, x_2, ...,x_P$ can be considered as independent one to the other, the previous relation is simplified accordingly:

$$u_y = \sqrt{\sum_{i=1}^{P} \left(\frac{\partial f}{\partial x_i} u_{xi} \right)^2} \tag{2}$$

3.3. Uncertainty component related to the errors of the sensors

In order to assess the influence of the metrological quality of the testing equipment on the quality of the final result, a mechanism for the quantification of this influence should be available. The lack of an explicit measurement model for the connection of raw experimental data or intermediate quantities with the calculated expected annual energy output makes the adoption of the conventional error propagation approach impossible, thus imposing the use of alternative approaches.

In the case of the CSTG method, the well-defined calculation procedure makes the Monte-Carlo simulation a suitable choice (BIPM, 2008b; Cox et al., 2006; Mathioulakis et al., 2012). This approach can be applied through the following steps:

I. The implementation of the experimental scenarios anticipated by the testing procedure of the system leads to a given number d of daily values H_i, ΔT_i and Q_i, $i=1,...,d$, for the intermediate quantities H, ΔT and Q.

II. On the basis of the metrological characteristics of the sensors used, the uncertainties characterizing the heat loses coefficient U_s, as well the values H_i, ΔT_i and Q_i, $i=1,...,d$, are calculated.

III. For each value of intermediate quantity, a large number N of random values is produced, the statistical properties of which are identical with the metrological characteristics of the simulated quantity. More specifically, the expectation and the standard deviation of the probability distribution assigned to each quantity, are equal to the measured value of this quantity and the associated standard uncertainty respectively.

IV. As resulting from step III, N distinct values of the expected energy output Q_l can be produced according to the methodology proposed in the testing standard.

V. From the N values of the expected energy output produced, the mean value Q_l and the standard deviation are calculated, the latter considered as a robust estimation of the standard uncertainty associated with the mean value.

In the case though of the DST method, the inability to automate the relevant calculations due to the form of the involved software (protected MSDOS executables), makes the choice of Monte-Carlo simulation prohibitive. Given also the inability to implement the law of error propagation, the only realistic solution would be the exploitation of appropriate sensitivity studies, aiming at the quantification of the effect of potential measurement errors on the final result (BIPM, 2008a; Lira, 2002).

The sensitivity analysis is based on the investigation of the variation of the final result (annual energy gain Q_l), as a function of the slight variations in the value of each measured parameter. For this reason, a slight variation dA is inserted in the experimental values of the parameter A, which have been recorded during the tests. Following, a new value $Q_l^{/}$ of the annual energy gain is calculated, as well as the difference of the new value to the initially calculated one, $dQ_l = Q_l^{/} - Q_l$. The sensitivity factor for the specific parameter can be estimated by the relation:

$$\frac{\partial Q_l}{\partial A} \approx \frac{dQ_l}{dA} \qquad (3)$$

In order for the specific estimation to be reliable, the relevant investigation has to be repeated for different values of dA, evenly distributed around the experimentally measured value. Moreover, the investigation has to be repeated for all parameters, the measured value of which influences the final result.

3.4. Imperfections of the energy model and related uncertainty

The energy model used, as any model of this type, can be considered to some degree as approximate, since it is evident that some kind of error is introduced through its use, potentially affecting the quality of the results of the testing method. The component of uncertainty related to the imperfections of the energy model, expresses the degree the model can explain the experimental data. Thus, in the case of CSTG method, the effectiveness of the model can be quantified by the standard estimation error of the fitting. In the case of DST method, an estimation of this uncertainty component is provided by the software of the expected annual energy gain calculation itself (Long Term Performance Prediction module of the software). According to the documentation accompanying the software, the relevant calculations use the cross correlation matrix of the energy model coefficients which have been iteratively determined through the fitting procedure (Spirkl, 1997).

3.5. Uncertainty related to the variance of the meteorological conditions

The expected energy output is calculated for a Typical Meteorological Year (TMY), statistically representative of the climatic conditions expected to take place on the installation site of the SDHWS. Nevertheless, the actual energy gain for the potential user strongly depends on the meteorological conditions which may occur during the actual operation of the system. Since these conditions are a priori different from the ones included in the TMY, an additional source of uncertainty related to the energy output value has to be considered.

The actual meteorological data of a significant number of years for the geographical area of installation site could be used for the estimation of the variance of the expected energy output due to the variation of meteorological conditions. For each of these meteorological years, the expected energy output of the system can be calculated and the respective component of the relative uncertainty can be estimated by the standard deviation of all the available calculated values of the energy output.

In most cases, the variability of meteorological conditions represents a significant source of uncertainty, compared to other uncertainty components (Mathioulakis et al., 2012). However, if test results are accompanied by a statement clarifying that the proposed value for the expected annual energy gain concerns only the adopted Typical Meteorological Year, the respective uncertainty coefficient can be ignored.

3.6. Calculation of overall uncertainty

Finally, the combined standard uncertainty characterizing the final result is computed as the square root of the algebraic sum of the individual variance contributions (BIPM et al., 2008a).

It has to be noted that the uncertainty characterizing a quantitative testing result depends on the specific conditions of the test performed, as well as on the characteristics of the device under test. From this point of view, the calculated uncertainty figures concern only the implemented test.

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