Validation of measurements using additional test sequences – an extension of the test procedure for solar collectors

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In the European Standard EN 12975 /1/ two different approaches for the determination of the thermal behaviour of solar collectors are described: The test method under steady state conditions and the method under quasi-dynamic conditions. Although both approaches are quite different one common item exists: a test is considered complete if all required test sequences have been performed. A validation of the determined parameters, in the way done for the testing of hot water stores, is not foreseen for collectors.
The present paper describes the selection and evaluation of a suitable validation sequence. In addition, criteria are introduced that help to decide whether the found parameter set describes the thermal behaviour of the collector satisfactory or not. The procedure is introduced for the example of a CPC collector with vacuum tubes.

1. Introduction

The reason why a validation procedure may be necessary for collectors is shown in Figure 1, where the measured collector output is plotted together with the calculated collector output.

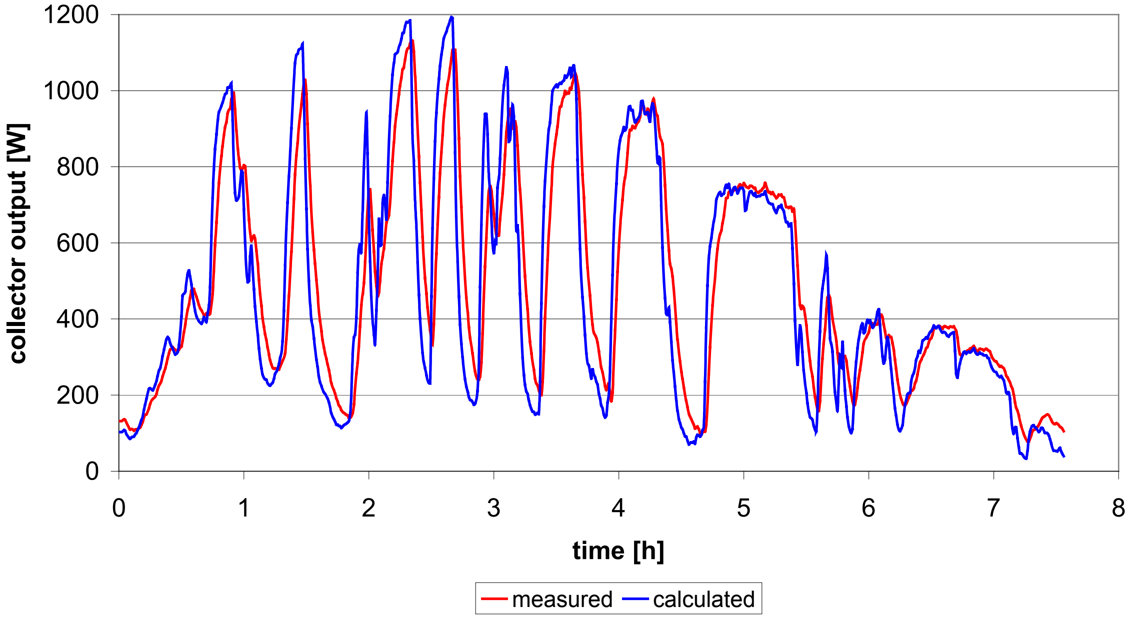

Figure 1: *Comparison of measured and calculated collector output*

The collector parameters obtained during the test can be used for performance predictions by a dynamic system simulation /2/. The results of the performance predictions are used to compare the collectors and are often the basis for the decision which collector will be installed. In Germany the results of the performance prediction serves, in addition, as a criterion whether a collector qualifies for government subsidies or not. Taking this into account it is reasonable to introduce a validation sequence within the thermal performance testing to prove that the dynamic behaviour of the collector in operation can be described by the determined collector parameters.

2. Definition of the test sequence used for validation

The requirements on the additional test sequence depend on the typical operation conditions (irradiance, collector temperature, angle of incidence, etc.) of a solar collector is as well as on the boundary conditions of the dynamic simulation (weather data and time step). The choice of the criteria and limiting values is based on the following considerations:

- a reasonable amount of solar irradiation must be taken into account
- a minimum fluctuation of solar irradiance is necessary to provide a check of the effective collector capacity
- to reproduce the fact that most solar collectors are operated together with a thermal store, an increase of the collector inlet temperature during the test sequence is required
- to check the conversion factor and the heat loss coefficients fluid temperatures close to ambient and significantly higher fluid temperatures are needed
- the angle of incidence must cover the typical range of daily operation
- the time step for recording the mean values must be such as that dynamic behaviour can be detected reasonably well

The criteria and limiting values used are summarised in Table 1.

Criteria	limiting values
Total solar irradiation in collector plane	> 8 MJ/m²
Standard deviation of the change in total irradiance with time dG/dt (variability of irradiance)	> 1 W/(m²s)
Increase of the inlet temperature	> 3 K/h
Difference of mean fluid temperature and ambient temperature	> 20 K
Angle of incidence[1] of beam irradiance θ	0° up to min. 50°
Time step dt during storage of mean values	< 60 s

Table 1: *Criteria and limiting values for the test sequence used for validation*

[1] For collectors with a biaxial incident angle behaviour the incident angle in east west direction has to be considered

3. Definition of the criteria of acceptance

The evaluation parameter used for the definition of the criteria of acceptance is the amount of heat transferred per square metre collector area during the test sequence, calculated according to equation (1).

$$q = \int \dot{q} dt \quad (1)$$

The area based collector output $\dot{q}$ is on the one hand determined on the basis of measured values (equation (2)) and on the other hand calculated according to equation (3), using the collector parameters obtained during the collector test.

$$\dot{q}_{\mathrm{m}} = \dot{m} c_p (\vartheta_{out} - \vartheta_{in}) \quad (2)$$

$$\dot{q}_c = \eta_0 K_{\Theta b}(\theta) G_b + \eta_0 K_{\Theta d} G_d - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - c_{eff} \frac{d\vartheta_m}{dt} \quad (3)$$

For acceptance of the obtained collector parameters two criteria have to be fulfilled:

1. The absolute value of the difference between calculated and measured heat supplied during the test sequence for validation must be less than 2% (equation 4)

$$\varepsilon_q = \frac{|q_c - q_m|}{q_m} < 0.02 \quad (4)$$

and

2. the sum of the absolute values of the difference in calculated and measured power per time step divided by the sum of the measured power per time step must be less than 5% (equation 5).

$$\varepsilon_p = \frac{\sum |\dot{q}_c - \dot{q}_m| dt}{\sum \dot{q}_m dt} < 0.05 \quad (5)$$

4. Implementation of the procedure

The procedure described above is applied for a CPC collector. The collector parameters gained during the collector test are summarised in Table 2.

η_0 [-]	$K_{\theta d}$ [-]	a_1 [W/(m²K)]	a_2 [W(m²K²)]	c_{eff} [J/(m²K)]
0.651	1.012	0.688	0.004	13060

Table 2: *Collector parameter*

The incident angle modifier $K_{\theta b}(\theta)$ of the investigated collector is calculated according to equation (6) /3/, the corresponding values of θ_l and θ_t are documented in Table 3.

$$K_{\theta b}(\theta) = K_{\theta b}(\theta_l, \theta_t) = K_{\theta b}(\theta_l, 0) \cdot K_{\theta b}(0, \theta_t) \quad (6)$$

angle of incidence θ	0	10	20	30	40	45	55	60	70	90
$K_{\theta b}(\theta_l,0)$	1.00	1.00	1.00	0.99	0.97	0.95	0.89	0.84	0.70	0
$K_{\theta b}(0,\theta_t)$	1.00	0.97	0.99	1.01	1.01	1.02	0.99	1.05	1.12	0

Table 3: *Incident angle modifier*

The characteristics of the test sequence used for validation are summarised in Table 4, a graphical overview is given in Figures 2 and 3.

Criteria	actual value
Total solar irradiation in collector plane	15.3 MJ/m²
Standard deviation of the change in total irradiance with time dG/dt (variability of irradiance)	1.1 W/(m²s)
Increase of the inlet temperature	5 K/h
Difference of mean fluid temperature and ambient temperature	27 K
Angle of incidence of beam irradiance θ	0° to 59°
Time step dt during storage of mean values	< 36 s

Table 4: *Actual values of the test sequence used for validation*

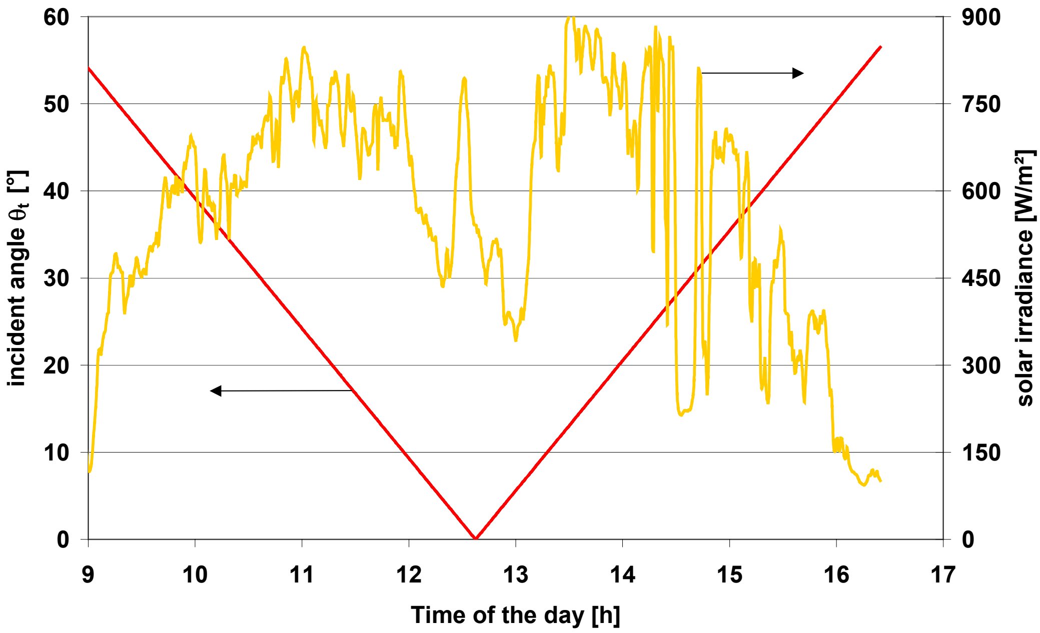

Figure 2: *Solar irradiance and transversal incident angle during the test sequence used for validation*

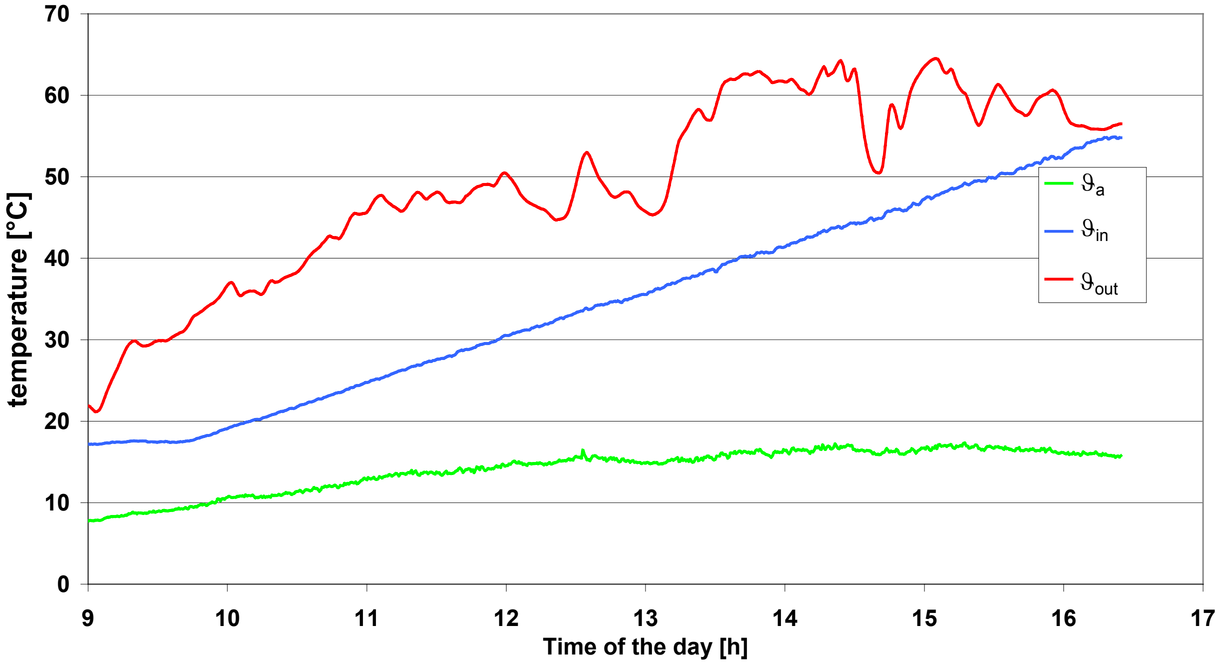

Figure 3: *Collector and ambient temperature during the test sequence used for validation*

Figure 4 shows the measured collector output together with the calculated collector output using the parameters gained during the collector test. In addition the difference between calculated and measured collector output is shown. When using the calculated collector output the heat transferred per square meter collector area is overestimated by about 1% (ε_q = 0.01). In case of the second criterion ε_p: the sum of the absolute values of the difference in calculated and measured power per time step divided by the sum of the measured power per time step, a deviation of about 3% can be observed. Considering the criteria defined in section 3 the set of collector parameters gained during the collector test can be accepted and used for performance prediction by dynamic system simulation.

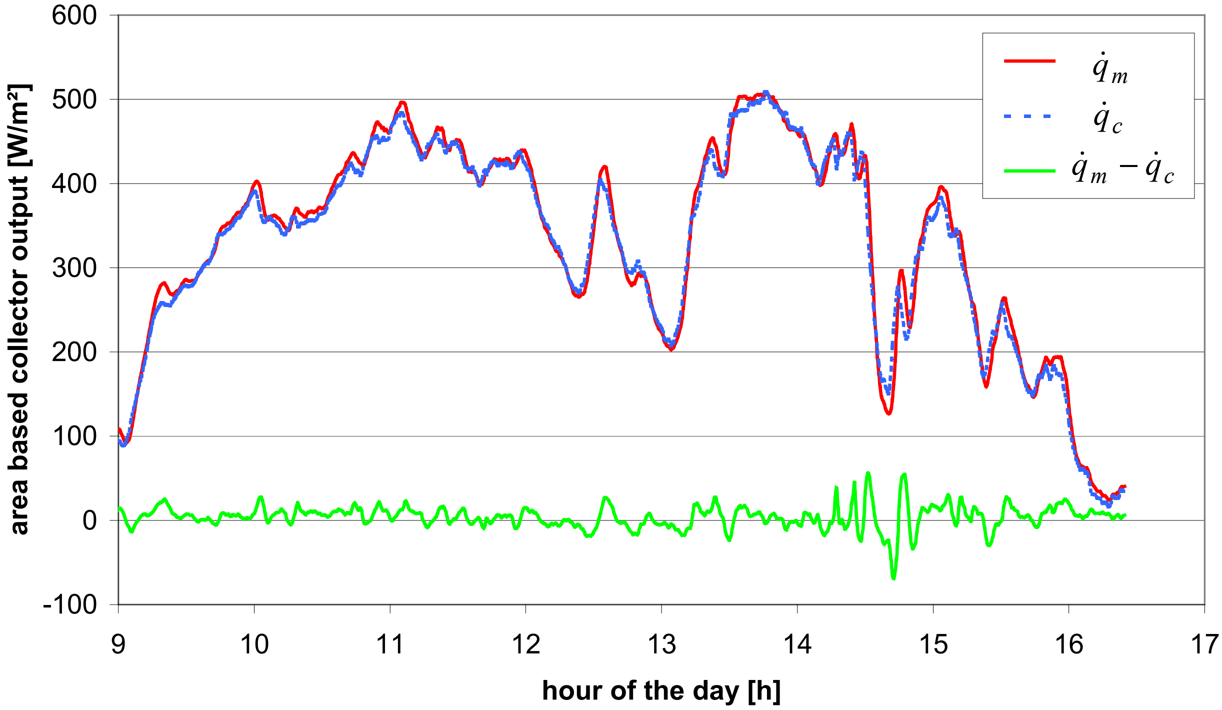

Figure 4: *Measured and calculated collector output during the test sequence used for validation together with the difference between measured and calculated collector output*

5. Conclusions

The validation of collector parameters obtained from collector testing is desirable if the parameters are used for performance prediction using dynamic simulation. For this purpose an additional test sequence and a set of acceptance criteria have been defined taking typical every day operation into consideration. This method is able to detect parameter sets that are not fully able to mirror the thermal behaviour of a collector under dynamic conditions. The implementation of the method shows for the presented example very promising results. It is strongly recommended to introduce the presented method into the EN 12975 standard.

Nomenclature

a_1	[W/(m²K)]	heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$
a_2	[W/(m²K²)]	temperature dependence of the heat loss coefficient
c_{eff}	[J/(m²K)]	effective collector capacity
c_p	[J/(kgK)]	specific heat capacity of heat transfer media
$d\vartheta_m/dt$	[K/s]	time derivative of the mean fluid temperature
G	[W/m²]	global solar irradiance
ε_q	[-]	difference of calculated to measured collector out put divided by measured collector output
ε_p	[-]	sum of the absolute values of the difference in calculated and measured power per time step divided by the sum of the measured power per time step
G_b	[W/m²]	beam irradiance
G_d	[W/m²]	diffuse solar irradiance
$K_\theta(\theta)$	[-]	incident angle modifier
$K_{\theta b}(\theta)$	[-]	incident angle modifier for beam irradiance
$K_{\theta d}$	[-]	incident angle modifier for diffuse irradiance
$\dot{m}$	[kg/s]	mass flow
η_0	[-]	zero loss efficiency
$\dot{q}$	[W/m²]	collector output
ϑ_a	[°C]	ambient temperature
ϑ_{in}	[°C]	inlet fluid temperature
ϑ_m	[°C]	mean fluid temperature
ϑ_{out}	[°C]	outlet fluid temperature
θ	[°]	incident angle of the beam irradiance

References

/1/ EN 12975-2:2001. Thermal solar systems and components – Solar collectors – Part 2: Test methods

/2/ EN 12977-2:2001. Thermal solar systems and components – Custom built systems – Part 2: Test methods

/3/ McIntire W. R., Factored approximations for biaxial incident angle modifiers. Solar Energy 29, 315-322, 1982