Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2

S. Fischer, H. Müller-Steinhagen
Institut für Thermodynamik und Wärmetechnik (ITW),
Universität Stuttgart, Pfaffenwaldring 6, D-70550 Stuttgart
Germany
E-mail: fischer@itw.uni-stuttgart.de

B. Perers
Vattenfall Utveckling AB, S-81426 Älvkarleby,
Sweden
E-mail: bengt.perers@vattenfall.com

P. Bergquist
Swedish National T&R Institute,
Sweden
E-mail: per.bergquist@sp.se

In April 2001 the new European Standard EN 12975:2000: "Thermal solar systems and components – Solar Collectors" was established. With the publication of this European standard all national standards, related to the same topic, have to be withdrawn by the nations of the European Community. Now only one standard for testing solar collectors is valid throughout Europe.
This European Standard specifies test methods for validating the durability, reliability and safety requirements for liquid heating collectors. The standard also includes two alternative test methods for the thermal performance characterization for liquid heating collectors. Apart from the well known test method under steady state conditions according to ISO 9806-1,3 and ASHRAE 93-77 the EN 12975 permits a quasi-dynamic test method for the thermal performance characterization of solar thermal collectors.
This paper presents the improved approach to outdoor performance testing of solar thermal collectors under quasi-dynamic test conditions. The test requirements and collector theory are closely connected to those long agreed on for steady-state testing, as described in e.g. ISO 9806-1,3 and ASHRAE 93-77. The most important effects for the all day performance of the collector are taken into account. The test method covers most collector designs on the market today (except ICS type). Only some correction terms are added to the basic collector models of the present steady-state test methods. Still this limited change will allow test data to be collected and used from whole days.
An important fact is that the collector model used for the parameter identification is written so that the error in collector output power is minimised. Therefore an accurate long-term prediction of the collector performance can be an integral part of the test method, where the same collector model and parameters are used for both testing and prediction.

1. INTRODUCTION

The knowledge of the thermal performance of a solar thermal collector is essential for the prediction of the yearly energy output of any solar thermal system. With the publication of the European Standard EN 12975 all national standards related to the topic of solar thermal collector testing have to be withdrawn. Therefore now only one standard exits throughout Europe. This guarantees the same test methods and thus comparable results for all collector tests performed in Europe. Apart from the test methods for validating the durability, reliability and safety requirements for solar liquid heating collectors the standard includes two alternative test methods for the thermal performance characterization of solar thermal collectors. Beside the well known method under steady-state conditions according to ISO 9806-1,3 and ASHRAE 93-77 the EN 12975 permits a quasi-dynamic test method for the thermal performance characterization of solar thermal collectors. This quasi-dynamic test method allows for a much wider range of test conditions as specified for the steady state method being at the same time fully comparable to the steady state method.

The basis for this test method is more than 15 years of collector testing research carried out in Sweden (Perers 1993, 1995 and 1997), (Hellström 1998). Important contributions to the test method have also been derived, during this period, from international co-operation within different IEA SH&C groups as Task III, VI and Task 14 and the German project VELS (Pauschinger, Drück, 1995).

2. THE COLLECTOR MODELS

As mentioned before the EN 12975 allows for two alternative test methods. The steady-state test method and the quasi-dynamic test method. This sections deals with the collector models of the two test methods and how the quasi-dynamic collector model is used for different collector types.

2.1. The collector model for the steady-state test methods

We start to describe the stationary or steady-state collector model in the EN 12975 standard. This model has been widely used both in testing (ISO 9806-1 and ASHRAE 93-77) and for simulation. If expressed as useful output power of the solar collector, the basic equation for the steady-state model for near normal incidence angle operation can be written as:

$$Q = F'(\tau\alpha)_{en}\, G - c_1\,(t_m - t_a) - c_2\,(t_m - t_a)^2 \tag{1}$$

Here, $F'(\tau\alpha)_{en}$ is the zero loss efficiency for global radiation at normal incidence and the c_1 and c_2 terms describe the temperature-dependent heat losses.
There are furthermore optional, separate test procedures for the determination of incidence angle dependence of the zero loss efficiency (IAM), here denoted $K_\theta(\theta)$ and the effective thermal capacitance of the collector, c_5 or $(mC)_e$. The parameter $(mC)_e$ is not measured, but calculated by weighting the capacities of the collector components. The full instantaneous equation based on all options of the steady-state test method can be written as:

$$Q = F'(\tau\alpha)_{en}\, K_\theta(\theta) G - c_1\,(t_m - t_a) - c_2\,(t_m - t_a)^2 - c_5\, dt_m/dt \tag{2}$$

This is still a clear weather or indoor solar simulator model. Only high irradiance levels and thus only low diffuse fractions are accepted in the test sequence. Furthermore it is required that the incidence angle is near normal, so that incidence angle effects can be neglected. This regulation limits the available outdoor testing time very much in variable climates and makes an outdoor test according to the steady-state test method very expensive.
This model has no correction term for diffuse radiation. This is needed in most simulation programmes for long term performance calculations. The solar radiation must be divided into beam and diffuse radiation and a separate incidence angle correction has to be known for the diffuse radiation.
No method for correction for non-stationary test conditions is described in the test procedure. Therefore very stable weather conditions are needed for each test point.

2.2. The collector model for quasi-dynamic collector testing

In the quasi-dynamic approach the first term of equation (2) is divided into two parts, the zero loss efficiency for beam radiation and the one for diffuse radiation. $F'(\tau\alpha)_{en}\, K_\theta(\theta)G$ is replaced by the sum of $F'(\tau\alpha)_{en}K_{\theta b}(\theta)G_b$ and $F'(\tau\alpha)_{en}K_{\theta d}(\theta)G_d$.
Furthermore the wind-dependence is modelled by two correction terms added to eq. (2). One term gives the effect on the zero loss efficiency ($- c_6uG$). This is significant for some plastic and rubber collectors. The other term models the wind influence on heat losses ($- c_3u(t_m-t_a)$).
After the addition of the long-wave "thermal" irradiance dependence of the heat losses, the collector model is complete and the full collector model for the useful output power of the collector is written as:

$$\begin{aligned} Q = {} & F'(\tau\alpha)_{en}\, K_{\theta b}(\theta)\, G_b + F'(\tau\alpha)_{en}\, K_{\theta d}\, G_d - c_6\, u\, G - c_1\,(t_m - t_a) \\ & - c_2(t_m - t_a)^2 - c_3\, u\,(t_m - t_a) + c_4\,(E_L - \sigma\, T_a^4) - c_5\, dt_m/dt \end{aligned} \tag{3}$$

The modelling of the long-wave irradiance dependence of the collector, as (c_4 (E_L- σ T_a^4)) is made in a similar

way as described in the basic ISO 9806-3, for testing of unglazed collectors, but here it is treated as a heat loss term. All additions to equation (2) inserted in equation (3) are based on long agreed collector theory. The coefficients in equation 3 are explained below:
c_1 = Heat loss coefficient at $(t_m - t_a) = 0$ is modelled as $F'\ U_0$ [$Wm^{-2}K^{-1}$]
c_2 = Temperature dependence of the heat losses, equal to $F'\ U_1$ [$Wm^{-2}K^{-2}$]
c_3 = Wind speed dependence of the heat losses, equal to $F'\ U_u$ [$Jm^{-3}K^{-1}$]
c_4 = Long-wave irradiance dependence of the heat losses, equal to $F'\ \varepsilon$ [-]
c_5 = Effective thermal capacitance, equal to $(mC)_e$ [$Jm^{-2}K^{-1}$]
c_6 = Wind dependence of the zero loss efficiency, a collector constant [sm^{-1}]
$K_{\theta d}$ = Incidence angle modifier for diffuse radiation, a collector constant [-]
$K_{\theta b}(\theta)$ = Incidence angle modifier (IAM) for direct (beam) radiation [-]
The basic modelling of incident angle dependence is made with the equation $K_{\theta b}(\theta) = 1 - b_0((1/\cos\theta_i - 1)$ as described in e.g. ASHRAE 93-77.
For collectors with special incident angle dependence, $K_{\theta b}(\theta)$ can not be described with a simple equation. Additional options are then available in the extended MLR method described in 4.2 below .

2.3. How to use the collector model for different collector types

The collector model as described in equation (3) will, to our knowledge, cover most collector designs available on the market today, except integral collector storage (ICS) collectors.
In an ICS collector the residence time of the fluid in the collector is often much longer than the prescribed averaging time of 5-10 minutes. Therefore the inlet and outlet temperatures will not reflect the internal energy content of the collector and an accurate capacitance correction is not possible with the simplified capacitance term proposed here. With a more elaborate capacitance correction term this can be solved.
For unglazed collectors, the use of the full collector model is mandatory. For other collectors the parameters to be used and presented in the results, will in general be given by the T-ratio of the initial regression (parameter identification). The T-ratio = (parameter value / standard deviation of parameter value) of the regression. The T-ratio should be greater than 2 for those parameters presented in the test results. Still for all types of collectors, the use of $F'(\tau\alpha)_{en}$, $K_{\theta b}(\theta)$, $K_{\theta d}$ and the coefficients c_1, c_2, and c_5 are mandatory and they should be identified.

3. TEST PERIOD AND PROCEDURE

The recommended test sequence, mounting and other test requirements, are closely connected to those widely accepted for steady-state testing of solar thermal collectors, as outlined in e.g. ISO 9806-1 and ISO 9806-3 and ASHRAE 93-77. The test conditions and the permitted deviation of the measured parameters during the test for the steady-state and the quasi-dynamic test are listed in Table 1.

Table 1: Test conditions and permitted deviations

	steady-state		quasi-dynamic	
Parameter	value	Deviation from the mean	value	Deviation from the mean
Global solar irradiance G	> 700 W/m²	± 50 W/m²	300 < G < 1100 W/m²	-
Incidence angle of the beam irradiance θ	< 20°	-	-	-
Diffuse fraction G_d/G	< 30 %	-	-	-
Surrounding air temperature t_a	-	± 1 K	-	-
Surrounding air speed u	3 m/s ± 1 m/s	-	-	-
Collector inlet temperature t_{in}	-	± 0,1 K	-	± 1 K

Basically the demand for suitable test data are the same for both types of approaches, and hence the recommended test sequence will allow also for conventional steady-state parameter identification, by obtaining and cutting out those measurement data sequences corresponding to steady-state requirements. However, the test database of course has to contain more and also the proper information, making it possible to identify the additional collector performance parameters now included in the collector model.
Compared to steady-state testing, the number of outdoor test days will be the same, i.e. 4 - 5 days (4 different inlet temperatures). But depending on the actual weather at the test site and time of year, steady-state testing may

need a lot more days, as the requirement for clear sky conditions around solar noon is very strong. This applies especially for middle and northern Europe.
The major difference however, is that the test data in this method are collected during the whole day, from early in the morning to late in the afternoon, as shown in Figure 1, instead of a few instantaneous values during some hours around solar noon each test-day with clear and stable enough weather.
By measuring during the whole day, e.g. enough information about IAM-dependence is obtained. In contradiction to steady state testing, also variable and partly cloudy conditions (Figure 2) during the test period are prescribed, making it possible to identify, e.g. the dependence of the diffuse part of the irradiance as well as the thermal capacitance of the collector.

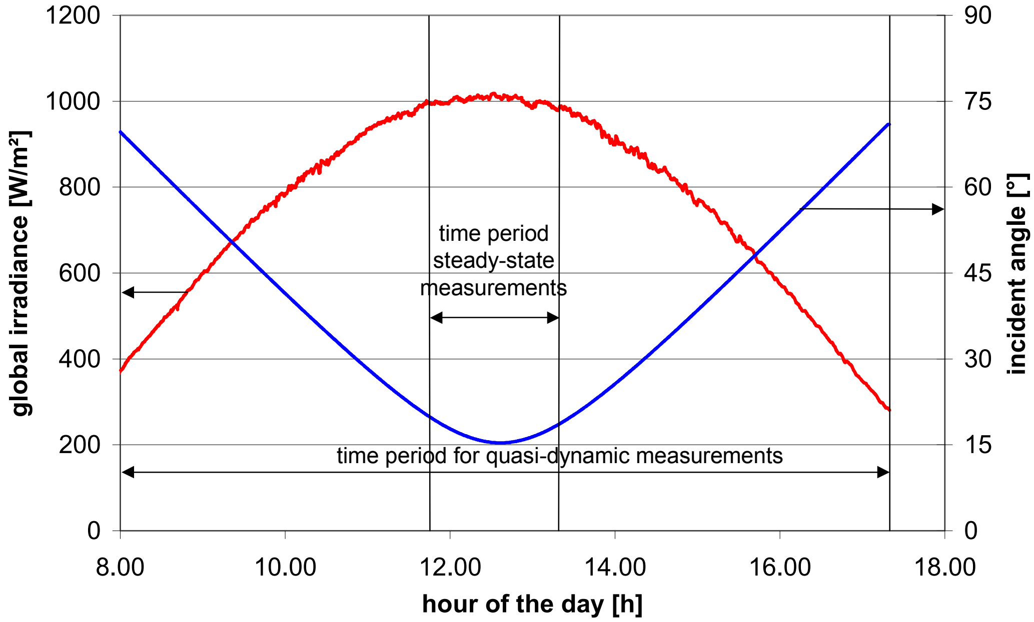

Figure 1: Acceptable time periods for steady-state and quasi-dynamic measurements on a clear day

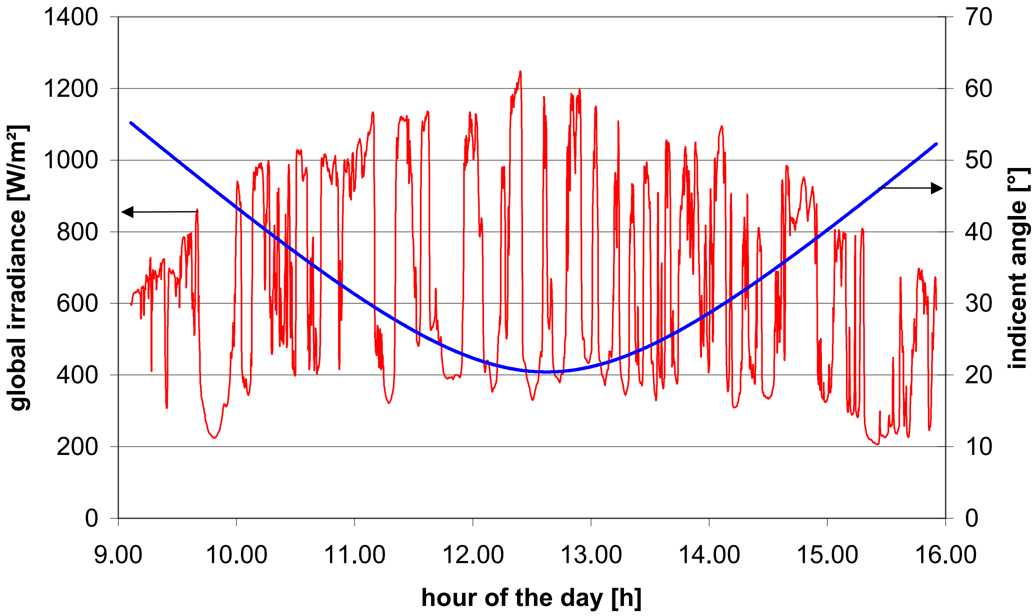

Figure 2: Time period only acceptable for quasi-dynamic measurements on a day with variable irradiance

4. THE PARAMETER IDENTIFICATION TOOL

The mathematical tool proposed for identification of the collector parameters, is denoted Multiple Linear Regression or "MLR". However, also very good experience have been made using the dynamic parameter identification. For a detailed mathematical description of the MLR method see (Draper 1981) and (Wiesberg 1985), for the dynamic parameter identification see (Spirkl 1990).

4.1. The standard MLR Method

The standard MLR method is the same mathematical tool as used for the evaluation of data in the steady-state standard (the least squares method). Linear means, that the model has to be written as a sum of terms where the parameters has to be a multiplier in front of the terms.
The equations behind the individual terms can therefore still be highly non-linear in spite of the description "linear" of the MLR method. In the collector parameter identification phase the collector model for the *thermal power output,* as in equation 3, is used. Therefore the derived parameter set will minimise the error in *useful power output* and not efficiency, as in steady-state testing. This is an important improvement of the method that is not so visible. This gives the best accuracy when later using the parameters and preferably also the same collector model in a simulation tool for prediction of the power and energy output of the collector.
The MLR-method allows for a free selection of data from the test data base, according to any test specification, before applying the MLR parameter identification. This selection can be made afterwards from measurements from a few test days. Using common spreadsheet software, e.g. EXCEL and LOTUS, even for an extensive database, the parameter identification will need only a few seconds of computer time, making MLR very versatile also for development and research.

4.2. The Extended MLR Method

Since several years, a special MLR method has also been developed for this application based on MLR with "dummy variables" (Weisberg 1995). This makes it possible to identify the same parameter in different subsets or ranges of the database. This offers the possibility to identify for example the zero loss efficiency angle by angle without the need to have an equation. Even in two axis directions θ_L and θ_t. $K_{\theta b}(\theta_i)$ in eq. (3) is then generalised and replaced by $K_{\theta b}(\theta_L,\theta_t)$.
Both the new and remaining other parameters can still be identified with a standard MLR software in the same run and at almost the same calculation time. This widens the range of collectors that can be tested accurately with this method and is especially useful for collectors as ETC (Evacuated Tube Collectors), CPC (Compound Parabolic Concentrator) or unglazed collectors with round separate absorber tubes. They can not be modelled accurately with the standard IAM equations. The derived IAM results can often be used directly in simulation programmes, as in the case of TRNSYS or WATSUN.

4.3. The dynamic parameter identification

Dynamic parameter identification is a method to find the best fit of a given parameterized model to a real system based on a time sequence of some measurable output. For a given set of forcing functions, $\mathbf{e}(t) = (e_1, e_2, ...)$, the modelled output, $y_{mod}(\mathbf{p},t)$, is a function of time and a set of parameter values, $\mathbf{p} = (p_1, p_2, ...)$. The best fit is given by the set of parameter values, which minimize the objective function $c(\mathbf{p})$, which, in principle, is the integral of the root mean square of the residual $r(\mathbf{p},t) = y_{mod}(\mathbf{p},t) - y_{exp}(t)$. However, before calculating $c(\mathbf{p})$, the high frequency components of the residual may be dampened using a low pass filter with the time constant τ_F. The purpose being to weaken the impact of measurement noise and imperfect transient modelling. Further, a period $[0,\Delta t_{skip}]$, long enough to let the influence of the initial state fade away is excluded from the calculation of $c(\mathbf{p})$. In this way the problem to determine the initial state is bypassed. The minimum of the objective function , $c(\mathbf{p})$, is searched in an iterative process. The method is attractive because it neither imposes any severe restrictions on the model nor on the time sequence of measured data, and the model can also used in simulations. The IEA Dynamic

System Testing Group has already demonstrated the feasibility of the dynamic parameter identification for tests of the performance of Solar Domestic Hot Water Systems and hot water stores.
The dynamic parameter identification method is especially useful for the identification of the collector parameters of collector with a asymmetrical incident angle behaviour as described in section 4.2.

5. COMPARISON OF THE RESULTS GAINED USING THE STEADY-STATE AND THE QUASI-DYNAMIC TEST METHOD

An essential qualification for an alternative test method is the compatibility of the gained results to the long established test method. The quasi-dynamic test method is build on a far more detailed collector model than the steady-state model, taking into account e.g. the incident angle behaviour of the thermal collectors. Due to these correction terms in equation (3) it is possible to predict the collector output power for any possible environment conditions, including the strict conditions demanded by the steady-state method.
The results gained by the two test methods can not be compared without the adjustment of the collector parameters found using the quasi-dynamic test method.
To conform these results with the presentation of the steady-state test the test results are presented in the form of a efficiency function and an efficiency curve which is calculated from the efficiency function using a global irradiance G = 800 W/m² and a diffuse fraction of 15%. The parameter dt_m/dt is set to zero and the incident angle θ to 15° to adjust to steady-state conditions at around solar noon. If the wind speed dependence of the heat losses and the zero loss efficiency are used in the collector model for glazed collectors the wind speed u = 3 m/s is used in the equation. If the sky temperature dependence of the heat loss coefficient is used in the collector model then $(E_L - \sigma T_a^4) = -100$ W/m² is used for the calculation. Equation 4 shows the described modification of equation (3) shown as an efficiency function.

$$\eta = F'(\tau\alpha)_{en} K_{\theta b}(15°)\,0.85 + F'(\tau\alpha)_{en} K_{\theta d}\,0.15 - c_6\; 3\cdot 1 - c_1 (t_m - t_a) \\ - c_2(t_m - t_a)^2 - c_3\, 3\,(t_m - t_a) - c_4\, 100/800 - c_5\cdot 0 \qquad (4)$$

Table 2 shows the test results of two flat plate collectors tested according the steady-state as well as according to the quasi-dynamic test method. To achieve the listed collector parameters of the quasi-dynamic test the above described procedure was applied. The efficiency curves of collector A are shown in Figure 3.

Table 2: Comparison of the test results according the steady-state and the quasi-dynamic test method

collector	method	η_0 [-]	c_1 [W/(m²K)]	c_2 [W/(m²K²)]	yearly energy gain [kWh/(m²year)]
A	steady-state	0.792	3.578	0.018	491
	quasi-dynamic	0.794	3.489	0.018	495
B	steady-state	0.776	3.823	0.012	485
	quasi-dynamic	0.787	3.749	0.013	484
C	steady-state	0.762	3.531	0.013	468
	quasi-dynamic	0.767	3.531	0.012	479
D	steady-state	0.729	3.289	0.010	454
	quasi-dynamic	0.736	3.184	0.013	466
E	steady-state	0.785	3.864	0.010	470
	quasi-dynamic	0.785	3.794	0.011	478
F	steady-state	0.765	2.938	0.014	496
	quasi-dynamic	0.774	3.084	0.013	502
G	steady-state	0.780	3.010	0.011	500
	quasi-dynamic	0.785	3.042	0.011	509
H	steady-state	0.724	3.464	0.008	430
	quasi-dynamic	0.727	3.179	0.013	456
I	steady-state	0.761	3.017	0.015	480
	quasi-dynamic	0.766	3.321	0.012	480

Table 2 shows that the zero heat loss efficiency $\boldsymbol{\eta_0}$ determined by the steady-state method is always slightly smaller than the one determined by the quasi-dynamic method. This is due to the fact that the mean incident angle as well as the diffuse fraction during the test have been greater than the 15° and 15% respectively.

The difference in the heat loss coefficients c_1 and c_2 between the two test methods can be neglected. If there is a significant difference in c_1 (e.g. collector I) it is compensated by the opposite difference in c_2.
To allow a more detailed comparison of the test results Table 2 shows, apart from the zero heat loss efficiency η_0 and the heat loss coefficients c_1 and c_2, the yearly energy gain of the collector. The yearly energy gain is predicted by a system simulation according BMWI (1995) using the simulation tool TRNSYS. The system simulation takes into account all identified collector parameters. This bears the advantage that a comparison of the thermal performance of different collector type can be done by using only one number: the yearly energy gain.
The used system is build up of a 300 liter thermal store, 135 liter are kept at a constant temperature of 60°C by the auxiliary heater, and an collector aperture area of 5m². The hot water load (200 l/day) is drawn at a temperature of 45°C and the reference weather data of Wuerzburg (Germany) is used.
The yearly energy gain based on the quasi-dynamic method is up two 2% higher that the one based on the steady-state method. This is basically due to the missing handling of the diffuse irradiance within the simulation of the steady-state results. Collector G denotes a difference of 6% in the yearly collector gain due to very pour incident angle dependence.

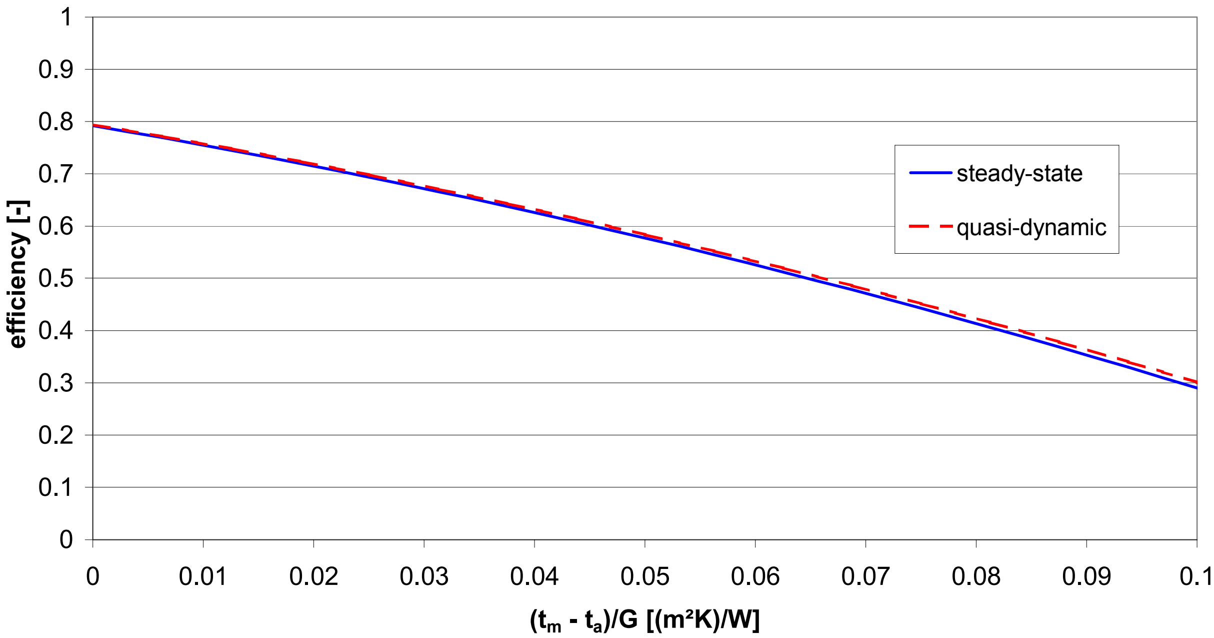

Figure 3: Comparison of the efficiency curves gained using the steady-state and the quasi-dynamic test method

6. CONCLUSIONS

The quasi-dynamic test method offers a much more complete characterisation of the collector and a much wider range of collectors can be tested within the same method, compared to the steady-state test methods.
At the same time, less restrictions in the test requirements makes it easier to find periods outdoors for testing: This leads to easier and cheaper tests, especially for places with varying climate conditions like middle and northern Europe.
These varying climate conditions, thus embedded in the test results, will also better reflect operating conditions encountered by the collectors in real service. This will improve the accuracy of collector performance predictions for application areas as design, research and collector development.
With the European Standard EN 12975:2000 there is now a guideline available that allows the test institute all over Europe to perform the collector test according to their very own weather conditions leading to comparable results. This is an important step towards the harmonization of the European solar market.

7. NOMENCLATURE

b_0	[-]	parameter for the characterization of the incident angle modifier of the beam irradiance
c_1	[W/(m²K)]	heat loss coefficient at $(t_m - t_a) = 0$
c_2	[W/(m²K²)]	temperature dependence of the heat loss coefficient
c_3	[J/(m³K)]	wind speed dependence of the heat loss coefficient
c_4	[W/(m²K)]	sky temperature dependence of the heat loss coefficient
c_5	[kJ/(m²K)]	effective thermal capacity
c_6	[s/m]	wind speed dependence of the zero heat loss efficiency
dt_m/dt	[K/s]	time derivative of the mean fluid temperature
E_L	[W/m²]	longwave irradiance
$F'(\tau\alpha)_{en}$	[-]	zero loss efficiency
G	[W/m²]	global solar irradiance
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
Q	[W/m²]	useful output power
u	[m/s]	surrounding air speed
η	[-]	efficiency
ϑ_a	[°C]	surrounding air temperature
ϑ_m	[°C]	mean fluid temperature
θ	[°]	incident angle of the beam irradiance
σ	[W/(m²K^4)]	Stefan-Boltzmann constant

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