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# TEST FACILITY FOR QUASI DYNAMIC COLLECTOR TESTS FOR THE CHARACTERIZATION OF THERMAL SOLAR COLLECTORS IN ACCORDANCE WITH THE INTERNATIONAL NORMS

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***Abstract:*** *A fundamental pre-requisite for the characterization and quantification of thermal solar collectors is the test for the determination of the parameters of the efficiency curve of that collectors. In the international context standard for the respective test procedures are given by the norms ISO 9806 and EN 12975-1.*

*Currently there is no test facility in Brazil, that is certified according to these norms. In view of a future certification a collector test stand able to perform tests in accordance to EN 12975-1 is under construction at the LABSOLAR Solar Energy Laboratory, (department of mechanical engineering at the Federal University of Santa Catarina.*

*EN 12975-1 is a dynamic test procedure that allows for shorter time requirements than the static test described by ISO 9806 which demands very strict climatic conditions and thus need excessive time. On the other hand the dynamic test requires a somewhat more demanding effort for the parameter extraction.*

*A main objective of the present work is the discussion of the test procedures in view the requirements of the accordance of the sensors involved and the of quality of the test results, i.e. the uncertainty of the collector parameters. The end use accuracy of the procedure is discussed using the uncertainty of the expected annual energy gain of the collector.*

**Key words:** solar collectors, efficiency measurement, multilinear regression.

## 1. INTRODUCTION

In order to foster the application of solar energy to cover the domestic hot water demand (DHW), reliable components and systems must be offered at the market. Regarding the collector as the central component certified performance characteristics must be available. For this purpose the Euro- and ISOnorm has developed standards for both quality and performance test [EN 12975-2; ISO 9806]. According to this standard, solar collectors must be subjected to a test to determine their efficiency curve.

The standard formulation under steady state conditions (constant radiation and operation conditions) for the efficiency curve is:

$$
\begin{aligned}
&\eta = \eta_0 - k_1 . \frac{\Delta T}{G} - k_2 \frac{(\Delta T)^2}{G} \\
&\textit{with}: \\
&\eta = \frac{\dot{Q}/A}{G} : \text{efficiency}, \\
&\Delta T = T_m - T_a, \quad T_m = \frac{T_{out} - T_{in}}{2}, \\
&\dot{\mathrm{Q}} = \dot{\mathrm{m}} \cdot (\mathrm{T}_{\mathrm{out}} - T_{in}) \cdot C_p \\
&T_{out} : \text{Colector outlet temperature } [{}^\circ\mathrm{C}], \\
&T_{in} : \text{Colector inlet temperature } [{}^\circ\mathrm{C}], \\
&T_m : \text{ Collector mean temperature } [{}^\circ\mathrm{C}], \\
&\mathrm{T_a} : \text{Ambient temperature } [{}^\circ\mathrm{C}], \\
&\dot{Q} : \text{usefull thermal power output } [\mathrm{Ws}], \\
&A : \text{collector surface } [\mathrm{m}^2], \\
&C_p : \text{Heat capacity for water} = \mathrm{f}(\mathrm{T_{in}}) \\
&\dot{m} : \text{Mass flux of water} = \mathrm{f}(\mathrm{T_{in}}, \dot{V})\, [\mathrm{kg/h}] \\
&\dot{V} : \text{Volume flux of water } [\mathrm{m^3/h}] \\
&G : \text{irradiance on the collector surface } \left[\mathrm{W/m^2}\right], \\
&k_1 : \text{heat transfer coeficient } [\mathrm{W/(m^2K)}], \\
&k_2 : \text{heat transfer coeficient } [\mathrm{W/(m^2K^2)}],
\end{aligned}
\tag{1}
$$

For the determination of the parameters characterizing the collector model, rules are included in the ISO standard [1]. In particular, the ambient conditions (irradiance and temperature) that allow for the application of the static model are strictly specified. Based on this model it is possible to estimate the energy gain of the respective collector, if the meteorological conditions are given and the constraints of the collector (operations temperature) by its application in a certain system are specified. With the results of the test and the subsequent simulation it is possible to determine a general and comparable quality standard of solar collectors and solar systems.

As the steady state test demands high stability of the climatic conditions, during the test, the time necessary to perform the test under outdoor conditions may get quite long. As an alternative to the steady state test, the Euro-norm EN 12975 permits to test the collector with a quasi-dynamic test. This test uses a more complete collector model that can handle variable climatic conditions and may thus lead to reduced time requirements for the tests, In this paper we present the quasi-dynamic test by the example of its application for different collectors: a German state of the art collector and a Brazilian collector. Utilized the measurement data from the ITW in Stuttgart we discuss the results and their calculated uncertainties.

## 2. COLLECTOR TEST PROCEDURES

### *2.1. Collector test under steady state conditions*

For the collector tests under steady state conditions according to ISO 9806[1] the parameters: $\eta_0$, $k_1$, $k_2$ of the model (eqn. 1) are obtained by linear regression from test data acquired from the operation of the collector under steady state conditions. The criteria for the environmental and operation conditions that have to be met are strict: global radiation > 700 W/m²; mass flux 0,02 kg/(m²s) +/- 1 %; collector inlet temperature +/- 0.1 K; ambient temperature +/- 1 K; incidence angle for the direct radiation < 30°; fraction of the diffuse radiation < 30%. These stable test conditions are either produced with an indoor collector test rig that works with artificial illumination or under thoroughly selected outdoor conditions. As the weather conditions for fulfilling the high requirements for stability are scarce, an outdoor test may need (also in Santa Catarina/Brazil) several month to be completed.

*To force the stable conditions during the outdoor test for longer periods, it is possible to use a collector sun tracker. The collector sun tracker keeps the collector surface always perpendicular to the direction of the sun, so that the necessary irradiance level can be maintained during longer time periods, provided that a clear sky situation is given.. The tracker however presents a remarkable additional investment.*

### *2.2. Extended collector model and collector test procedure under quasi-dynamic conditions*

Under outdoor conditions in general it is difficult to assure steady state conditions (see 2.1) for the solar radiation. Thus the collector operation in general varies and the collector performance has to be described by a dynamic equation. To deal with changing operation temperatures a term taking into account the temperature gradient and the heat capacity of the collector has to be taken into account. To deal with the change of the optical performance of the collector with varying incidence angles of the irradiance, parameters describing the angular response of the collector to the direct and the diffuse irradiance are used. Eqn. 2 shows the extended equation for the collector efficiency containing terms for the varying absorber temperature and angular the response characteristics. This equation contains 6 parameters ($\eta_0$, $\eta_0{*}b_0$, $\eta_0{*}M_{diff}$, k1, $k_2$, $C_{eff}$) that have to be determined.

$$\eta = \frac{\eta_0 \cdot G_b}{G} - \frac{\eta_0 \cdot b_0\left(\frac{1}{\cos\theta} - 1\right)G_b}{G} + \frac{\eta_0 \cdot M_{diff} \cdot G_d}{G}$$

$$- k_1 . \frac{\Delta T}{G} - k_2 \frac{(\Delta T)^2}{G} - \frac{C_{eff}}{G}\frac{dT_m}{dt}$$

*with* :

$\eta = \frac{\dot{Q}/A}{G}$ : efficiency,

$T_m = \frac{T_{out} + T_{in}}{2}$,

$\Delta T = T_m - T_a$

$\dot{Q}$ : usefull thermal power output [Ws],

$A$ : collector surface $[m^2]$,

*and* :

$\theta$ : incidence angle of the direct solar irradiance [°],

$G_b$ : beam irradiance on collector surface $[W/m^2]$,

$G_d$ : diffuse irradiance $[W/m^2]$,

$G$ : global irradiance on the collector surface $[W/m^2]$,

$T_m$ : mean collector temperature [°C],

$T_{out}$ : outlet temperature [° C],

$T_{in}$ : inlet temperature [° C],

$T_a$ : ambient temperature [° C],

6 regression coefficients :

$\{\eta_0\}$ : zero loss efficiency [-],

$\{\eta_0 \cdot b_0\}$ : $b_0$ = factor to determine the incidant [-],
angle modifier of the beam irradiance [-],

$\{\eta_0 \cdot M_{diff}\}$ : $M_{Gd}$ = modifier for diffuse radiation [-],

$\{k_1\}$ : heat loss coeficient $[W/(m^2K)]$,

$\{k_2\}$ : heat loss coeficient $[W/(m^2K^2)]$,

$\{C_{eff}\}$ : effective thermal capacity $[J/(m^2K)]$

(2)

With the development of a test procedure that is called "**quasi dynamic**" collector test (test with constant input temperature and variably output temperature), it is possible to calculate the collector parameters of eqn. (2) with the measured data of the outdoor collector test using a less restricted range of operational conditions (global radiation between 300 and 1100 W/m²; mass flux 0,02 kg/(m²s) +/- 1 %, collector inlet temperature +/- 1 K).

As all parameters appear as linear in eqn. 2, they can be extracted from sets of the data of the ambient conditions and the collectors operation (flow rate, inflow temperature) and performance (outflow temperature) by a multi linear regression. This procedure can be performed by standard software tools, e.g. spread sheet programs like Excel$^{TM}$ and Lotus$^{TM}$.

The set of ambient conditions comprises, besides the ambient temperature, the beam radiation, the diffuse radiation and the incidence angle for the beam radiation. The beam radiation can either be measured or be derived from the difference between the global and diffuse radiation data. The incidence angle for the beam radiation (angle between the sun direction and the collector orientation) can be calculated with a standard set of astronomic equations.

The quasi-dynamic-collector test is to be realized under outdoor conditions and works with in a fixed installation of the collector. The constraints for the ambient conditions are less strict (global irradiance G: 300 W/m² < G 1100 W/m²). The test only requires a constant fluid flux through the collector. With the constant flux, the collector passes various test sequences with various input temperatures. In each sequence the input temperature of the collector has to be held constant (+/- 1 K).

As the restrictions for the ambient conditions are less severe, the time requirements for the quasi dynamic collector test are reduced as compared to the static test.

The standards for the measurement conditions, the quality requirements for the equipment (see table 1) and the procedure for the parameter determination are given by EN 12975-2 [2].

### *2.2 Equipment for the quasi-dynamic test*

A schematic overview on the equipment necessary to perform the collector test discussed is given in fig 1. It consists of temperature sensors (e.g. PT100), a precision flux meter, pyranometers (e.g. Kipp and Zonen CM11), radial ventilation unit and a device able to maintain a constant fluid flux and temperature like a Kyrostat or a conventional cooling unit which may be combined with a temperature- and flux-controlling unit.

The basic requirements for the data range and the accuracy of the instrumentation used in the test are given in table 1.

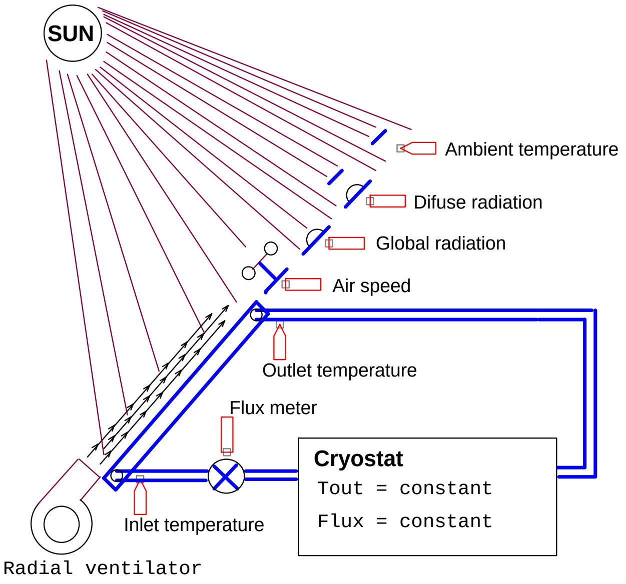

Figure 1: Schematic diagram for the set up of a test rig for the quasi-dynamic collector test (with sensor and control-equipment)

| Parameter | Range | Uncertainty |
|---|---|---|
| Input temperature: | 10...100 | ± 0.1 °C |
| Output temperature: | 10...110 | ± 0.1 °C |
| Ambient temperature: | 0...50 | ± 1 °C |
| Global radiation | 0.1000 W/m² | ± 2 % |
| Diffuse radiation: | 0....500 W/m² | ± 5 % |
| Water flux: | 40.....160 kg/h | ± 1 % |
| Air speed over the | | |
| Collector area: | 0..5 m/s | ± 0.5 m/sec |

Table 1: Requirements for the data range and the accuracy of the instrumentation for the collector test according to EN 12975-2.

## 3. COLLECTOR TEST ACTIVITIES IN THE LABSOLAR-LABORATORY

The LABSOLAR-“laboratory of solar energy” of the Federal University of Santa Catarina in Florianópolis already performs outdoor collectors tests according to a steady state procedure (see fig. 2).

Figure 2: Actual status of the collector test rig at the "Universidade Federal de Santa Catarina" in Florianópolis

This test stand is currently being upgraded to an installation that can perform the quasi-dynamic test according to EN 12975-2.

To quantify the expected benefit of the application of the quasi-dynamic test procedure with respect to time requirements we have analyzed the meteorological conditions at Florianópolis regarding the hours favorable to perform the different tests. With the data for the ambient conditions at Florianópolis (year 1999) and the test conditions of the static- and the quasi-dynamic-test the possible yearly test hours where calculated. For the static test only about 373 test hours per year are expected at Florianópolis.. For the quasi-dynamic test this value rises to 2121 test hours per year. Calculated with 53 test hours/test for the dynamic test, we expect to be able to execute around 80 collector tests per year using two collector test rigs. It has to bee noted that the calculation was executed with the hourly mean values of the ambient data and so the 373 test hours of the static test can still be reduced if solar irradiance deviates from the mean values that pass the test conditions of the static test.

## 4. AN EXAMPLE FOR QUASI DYNAMIC COLLECTOR TEST

To obtain a reference for both, the operation of the test rig and the subsequent parameter evaluation a commercial collector from a Brazilian manufacturer has been tested at an established test facility. For this purpose the ITW (Institut für Wärmetechnik) at the University of Stuttgart (Germany) was chosen for its experience with dynamic collector tests (see e.g. [3]). The collector was transferred to Germany and the test measurements could be concluded within 8 days.

Based on the set of data for the ambient conditions and the collector performance the identification of the collector parameters was performed [5]. For this purpose, the equation for the collector efficiency (2) is transformed to an equation (3) describing the useful thermal power output of the collector.

$$\dot{Q}_{reg} = \left[\left[\ (\eta_0)\cdot[G_b] - (b_0\cdot\eta_0)\cdot\left[\frac{1}{\cos\theta}-1\right]\cdot[G_b] + (M_{diff}\cdot\eta_0)\cdot[G_d] - (k_1)\cdot[\Delta T] - (k_2)\cdot[\Delta T^2] - (C_{eff})\cdot\left[\frac{\partial T_m}{\partial t}\right]\right]\right]\cdot A$$

$$\dot{Q}_{me} = [\dot{m}]\cdot C_p\cdot[\Delta T] = \text{measured power}$$

A : collector area [ $m^2$ ]

$C_p$ = heat capacity of water $\left[\frac{J}{kg\,K}\right]$

$\theta$ = incidence angle of the direct irradiance

[ ] = measured data, data derived from the measurement conditions

( ) = coefficients to be derived linear regression

(3)

The parameters to be determined that appear as coefficients in eqn. 3 [marked by ( )] can now be derived by multi-linear regression. The measured input data for the regression are the values in the [ ]–parenthesis. The spreadsheet programs Excel$^{TM}$ was applied for this task. This tool also delivers information on the uncertainties of the coefficients resulting from the regression in form of a 95% confidence interval (see section 6). In this procedure information on the accuracy of the individual experimental values does not enter explicitly, and are thus treated with equal weights.. The subsequent discussions on the uncertainties of the efficiency curve an the annual energy gain are based on these confidence information.

Table (2) and table (3) show the sets of the output of the regression for two collectors that are used in this paper.

| | coefficient | uncertainty | units |
|---|---|---|---|
| **eta0=** | **0.715** | **0.0072** | **[ - ]** |
| **b0=** | **0.163** | **0.0173** | **[ - ]** |
| **IAMdfu=** | **0.882** | **0.0197** | **[ - ]** |
| **k1=** | **5.985** | **0.4524** | **[ W / $m^2$ K ]** |
| **k2=** | **0.0360** | **0.0101** | **[ W / $m^2$ $K^2$ ]** |
| **Ceff=** | **12686** | **987.2** | **[ J / $m^2$ K ]** |

Table 2: Regression coefficients and their 95% uncertainties as given by the Excel$^{TM}$ spread sheet tool for a Brazilian test collector

| | coefficient | uncertainty | units |
|---|---|---|---|
| **eta0=** | **0.817** | **0.00663** | **[ - ]** |
| **b0=** | **0.149** | **0.01240** | **[ - ]** |
| **IAMdfu=** | **1.002** | **0.05425** | **[ - ]** |
| **k1=** | **4.041** | **0.24946** | **[ W / $m^2$ K ]** |
| **k2=** | **0.0065** | **0.00334** | **[ W / $m^2$ $K^2$ ]** |
| **Ceff=** | **7677.77** | **1292.85** | **[ J / $m^2$ K ]** |

Table 3: Regression coefficients and its 95% uncertainties as given by the Excel$^{TM}$ spread sheet tool for a German "state of the art" collector.

## 5. DISCUSSION OF THE TEST RESULTS

### *5.1. Normalization*

As can be seen from eqn (2) and (3) the efficiency and thus the power output of a collector is dependent in a complex way on the operation temperatures and the ambient conditions, including the composition of the global incident irradiance from the contribution from its direct and a diffuse component. For a standard representation of the efficiency characteristics of a collector, settings of 800 W/m² for the global irradiance and 120 W/m² for the diffuse are used. For the incident angle a value of 15° or 0° is used. With these settings, the parameters $\eta_0$ , $M_{diff}$ and $b_0$ condense to a unique normalized value $\eta_{0\_norm}$, which describes the collector efficiency under the these conditions when operated at a temperature equal to the ambient (see eqn (4)).

$$\eta_{0\_norm} = \eta_0 \cdot \left( \frac{G_b}{G} \cdot IAM_{dir\_15} + \frac{G_d}{G} \cdot M_{Gd} \right)$$

$$with:$$

$$IAM_{dir\_\theta} = 1 - b_0 \cdot \left( \frac{1}{\cos\theta} - 1 \right) \tag{4}$$

It is the convention, to present the efficiency curves as given by eqn. 5:

$$\eta_{norm} = \eta_{0\_norm} - k_1 \cdot \frac{T_m - T_a}{G} - k_2 \cdot \frac{(T_m - T_a)^2}{G} \tag{5}$$

in plots, that use the ration of the temperature difference (Tm-Ta) to the global incident irradiance as x axis. 'Doing This, the efficiency characteristics for different irradiances would collapse to one straight line for a negligible 3. term on the right hand side of eqn. 5. The efficiency curves for the two collectors discussed above are given in figures 3 and 4.. The uncertainty information also given in this plot will be discussed in the next section.

To relate the values of $\eta_0$, k1 and k2 for the two examples discussed to those that appear in the population of collectors on the market, table 4 gives a summary of the range of parameters derived from a sample of 477 different commercial models.

Table 4 : Range of collector coefficients taken from data of 477 collectors steady state collector tests executed at the SPF "Institut für Solartechnik" in Switzerland.

| | range | units |
|---|---|---|
| $\eta_0$ | 0.421.....0.959 | [ - ] |
| k1 | 0.87.......12 | [ W / m² K ] |
| k2 | 0.005....0.047 | [ W / m² K ²] |

In view of the broad range of parameter values that can be expected, and the complex method of their determination, the next section will discuss the uncertainties of the collector parameters and more specifically the associated uncertainty of the collector's efficiency curve.

## 6. UNCERTAINTY INTERVALS FOR THE MODELED EFFICIENCIES

With the set of collector coefficients and the respective ambient conditions the normalized steady state efficiency curve η(ΔT, G) using equations (4) and (5) was calculated (see fig. 4). In this section we present a simplified calculation of the 95% uncertainty for the modeled efficiencies taking into account the uncertainties of the estimated model parameters as given the tool Excel$^{TM}$ as described in section 4..They are used for the estimation of the uncertainty of the calculated efficiency applying eqn 6.

$$U_\eta^2 = \left( \frac{\partial \eta}{\partial \eta_0} \cdot U_{\eta\_0} \right)^2 + \left( \frac{\partial \eta}{\partial b_0} \cdot U_{b0} \right)^2 + \left( \frac{\partial \eta}{\partial M_{G_{diff}}} \cdot U_{M_{diff}} \right)^2 + \left( \frac{\partial \eta}{\partial k_1} \cdot U_{k1} \right)^2 + \left( \frac{\partial \eta}{\partial k_2} \cdot U_{k2} \right)^2 + \left( \frac{\partial \eta}{\partial C_{eff}} \cdot U_{C_{eff}} \right)^2 \tag{6}$$

Doing this, implicitly we make the following assumptions

I.) In the analyses of uncertainty for the steady state collector test and the quasi-dynamic collector test it was assumed, that all systematic errors of the sensors are compensated.

II.) The regression coefficients of the multi-linear regression are statistically independent to each other

In addition it has to be remarked that the estimation of the collector parameters and their uncertainties as it is presented here has to be improved by taking the uncertainty of the basic measurements explicitly into account. Respective procedures are e.g. presented by [6],[7] and [8] for the case of the static test procedure and the collector model according to eqn.1.

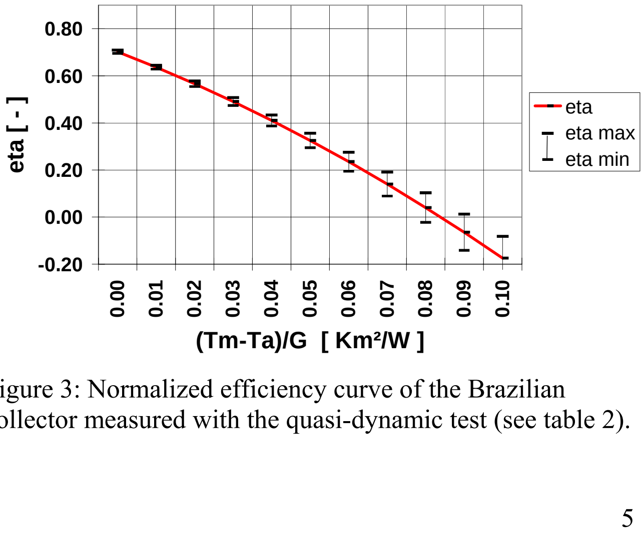

Figure 3: Normalized efficiency curve of the Brazilian collector measured with the quasi-dynamic test (see table 2).

Eta max and Eta min give the 95% confidence interval for the calculated efficiency.

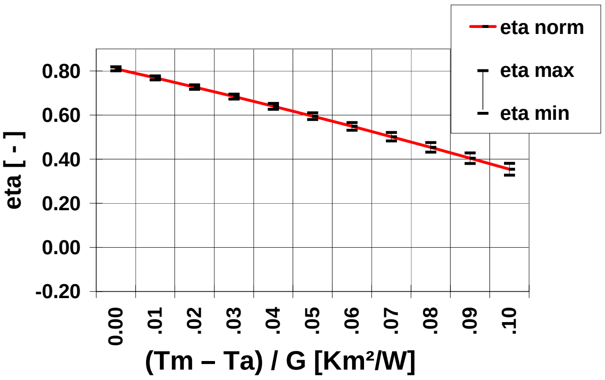

Figure 4: Same presentation as fig. 3, but for the German state of the art collector (see table 3).

## 7. THE ANNUAL ENERGY GAIN AND ITS UNCERTAINTY

To perform a simple comparison of different collectors in view of their possible energy gain at a certain location, an assumption on the operation conditions i.e. fixed mean collector temperature can be taken. Using the normalized collector equation (eqn. 5) and a set of data describing the meteorological conditions, the energy gain can be estimated on an hourly basis. Usually hourly data sets of the global irradiance and ambient temperature as given by a “typical meteorological year” (TMY) data set are used as basic input for this purpose.

The hourly power output of the collector can be calculated as described by eqn.7. The annual energy gain results from the summation of the respective hourly energy gain over all hours with a positive gain (eqn. 8).

$$\begin{aligned}\dot{Q}[i] &= \eta[i]\cdot G[i]\cdot A\\ &= A\cdot\left[G[i]\cdot\eta_0 - k_1\cdot(T_m - T_a[i]) - k_2(T_m - T_a[i])^2\right]\end{aligned} \tag{7}$$

$$E = \sum_{1}^{8760}\begin{cases}\dot{Q}[i]\cdot 1h & \text{for}\,\dot{Q}[i] > 0\\ 0 & \text{else}\end{cases} \tag{8}$$

Eqn. (7) can be reformulated to eqn. (8) with the condition, that the averages are only calculated from data of the N hours with a positive energy gain.

$$E = A\cdot N\cdot 1h\cdot(\overline{G_{tilt}[j]}\cdot\eta_0 - k_1\cdot(T_m - \overline{T_a[j]}) - k_2(T_m - \overline{T_a[j]})^2) \tag{9}$$

Using this relation and the uncertainties of the collector parameters as Using this relation and the uncertainties of the collector parameters as discussed above, the associated uncertainty of the energy gain can be calculated applying equation (10).

$$U_E^2 = \left(\frac{\partial E}{\partial\eta_0}\cdot U_{\eta_0}\right)^2 + \left(\frac{\partial E}{\partial k_1}\cdot U_{k1}\right)^2 + \left(\frac{\partial E}{\partial k_2}\cdot U_{k2}\right)^2 \tag{10}$$

In the case study presented here, we use an annual set of hourly meteorological data from Florianópolis for the assessment of the energy gain and its uncertainty. As we assume a collector installed with a tilt equal to the latitude of the location (27° South for the case of Florianópolis) the radiation data measured on the horizontal surface have to be transformed to irradiance values on the tilted plane.

The mean collector temperature used as input to these calculations is varied from 30° C to 70°C. The energy gain and its uncertainty under these conditions are given in fig. 5.

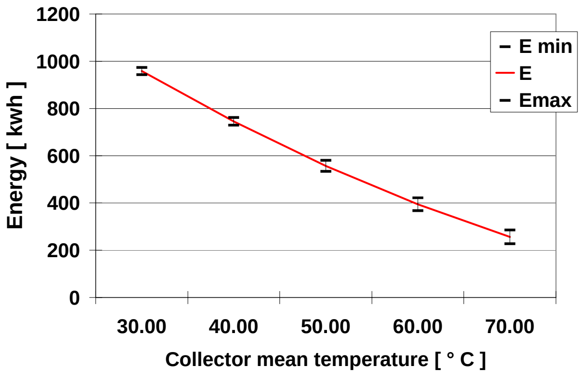

Figure 5: Energy production of the Brazilian collector calculated with the collector coefficients elaborated with the quasi-dynamic test procedure. The upper and the lower bound of the 95% confidence interval are given by E max and E min .

## 8. SUMMARY AND OUTLOOK

Test procedures for solar collectors according to EN 12975-2 and ISO 9806 were presented. Compared to the strictly static test described by ISO 9806, the quasi dynamic outdoor tests with EN 12975-2 which works with a more elaborated dynamic model of the solar collector can be performed more rapidly. Because of its high repeatability it was accepted as a standard test. A Brazilian collector was tested as a reference at the Test Centrum ITW of the University of Stuttgart in Germany. The results are compared to a German state of the art collector.

With the test results, the yearly energy output was calculated under the climatic conditions of the site of Florianópolis. Both, the uncertainties of the normalized efficiency curve and the yearly energy output were calculated.

A test facility according to both, EN 12975-2 and ISO 9806 will be implemented at the University of Santa Catarina at LABSOLAR. For an in depth comparison of the two test methods, the quasi-dynamic and steady state test will be executed with the same collector, with the same test facility and most possible with similar climatic conditions.
The uncertainties of these tests will be analyzed taking the precision of the instruments explicitly into account by applying and extending methods, that a currently discussed in the literature for the case of the steady state test.

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