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401 - Solar thermal collector yield – experimental validation of calculations based on steady-state and quasi-dynamic test methodologies

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Abstract

The characterization of collector efficiency is the fundamental tool for long term calculation of collector yield. It is, thus, one of the most important inputs in software tools aiming the design of solar thermal systems.

Presently two test methodologies are available for characterization of the efficiency of glazed collectors: i) steady state test and ii) quasi-dynamic test, methodologies based in different model approaches to a solar collector, providing different collector efficiency curve parameters and, consequently, imposing different power calculation algorithms.

Moreover, Horta et al (2008) demonstrated that the use of the collector efficiency curve derived from steady state test method is not enough for a thorough characterization of the long term performance of a collector.

The present work takes into account the introduction of the above referred test methodologies in the European Test Standard for Solar Thermal Collectors, and aims at clarifying how each test results should be used in long term thermal performance calculations.

The paper presents a synthesis of the different efficiency parameters provided by each test methodology and corresponding algorithms, applicable in the calculation of delivered power. Application of these algorithms to two days of measured data allows for a comparison of the results obtained with these different methodologies.

For validation purposes, results of tests performed on a CPC type collector with a concentration ratio C=1.72 are used. Measurement sequences are used to validate the calculation of power delivered by the collector using both algorithms based on steady-state methodology (with and without correction) and quasi-dynamic methodology.

Keywords: solar thermal energy; efficiency curve parameters; solar system simulation; long term performance assessment

1. Introduction

The characterization of collector efficiency is the fundamental tool for long term thermal performance calculation, i.e. collector yield, and for design of solar thermal systems. It is, thus, one of the most important inputs in software tools aiming at the design of solar thermal systems.

Presently two test methodologies are available for characterization of the efficiency of glazed collectors: i) steady state test methodology according to EN 12975-2: section 6.1 and ii) quasi-dynamic test methodology according to EN 12975-2: section 6.3.

It should be stressed that these methodologies, based on different model approaches for a solar collector, provide different collector efficiency curve parameters and, consequently, impose different algorithms for calculation of the power (and energy) delivered by solar thermal collectors.

In recent studies, Horta et al. (2008) demonstrated that the use of the collector efficiency curve derived from steady state test method is not enough for a thorough characterization of the long term performance of a collector, especially if its optical characteristics differ from the simplest flat plate collector.

Considering that, at present, steady-state tests are more commonly used and the majority of available collectors are characterized by steady state based efficiency curve parameters, a methodology for correction of power/energy results obtained with those parameters was proposed by Horta et al. (2008).

Recently, in project NEGST (Carvalho et al., 2006) it was also highlighted that for a correct characterization of stationary collectors with special optical characteristics or for tracking collectors, the quasi dynamic test method is the most appropriate test methodology.

The paper presents a synthesis of the different efficiency parameters provided by each test methodology and corresponding algorithms, applicable in the calculation of delivered power (see section 2). A validation of the methodology proposed by Horta et al. (2008), for the correction of long term performance calculations based on steady-state parameters, is also presented, after the results of tests performed on a CPC type collector with a concentration ratio C = 1.72.

2. Power calculations based on available test methodologies

Collector instantaneous efficiency η is defined as a ratio between the useful heat $\dot{Q}$ delivered and the hemispherical irradiance G_{col} on the collector aperture A_a, according to (Rabl, 1985):

$$\eta = \frac{\dot{Q}}{A_a G_{col}} = \frac{\dot{q}}{G_{col}} \qquad (1)$$

The hemispherical radiation G_{col} reaching the collector aperture plane, to which the collector instantaneous efficiency is referred to, is calculated by the summation of the different components of radiation, for a given beam radiation incident angle θ, and the plane tilt angle β, according to (Rabl, 1985):

$$G_{col} = I\cos\theta + D(1+\cos\beta)/2 + R_g(1-\cos\beta)/2 \qquad (2)$$

where the ground reflected component - $R_g = \rho_g G$ - depends both on the global radiation G reaching the horizontal (ground) plane and on the ground reflectivity (albedo) ρ_g.

As known, in the steady-state efficiency test (EN 12975-2; section 6.1) the collector efficiency curve is described by four parameters (considering a glazed collector): the optical efficiency η_0, a global heat loss coefficient a_1 and (in the second order approach) a temperature dependent coefficient for the global heat loss coefficient a_2. The test includes also the measurement of incidence angle modifiers $K(\theta)$ based on hemispherical irradiance, to be used in instantaneous power calculations.

In the quasi-dynamic efficiency test (EN 12975-2; section 6.3), the collector efficiency curve is described by five parameters (considering glazed collectors) and the incidence angle modifier values based on beam radiation. The five parameters are: the optical efficiency for beam radiation η_{0b}, the incidence angle modifier for diffuse radiation K_d, a global heat loss coefficient c_1, a temperature dependent coefficient for the global heat loss coefficient c_2 and a dynamic response coefficient c_5 representing the effective heat capacity of the collector.

Besides the treatment of the dynamic response of the solar collector to temperature changes included in the quasi-dynamic test methodology, the major difference to the steady-state methodology lies in the decoupling of the radiation components, allowing the separation of effects affecting differently each of those components (e.g. optical effects, as referred by NEGST (2006) and Horta et al. (2008)).

According to EN 12975-2; section 6.1 the calculation of instantaneous collector power from steady-state efficiency curve parameters follows equation 3:

$$\dot{Q}_{ss} = \eta_0 K(\theta) G_{col} A_a - a_1 \left(T_f - T_a\right) A_a - a_2 \left(T_f - T_a\right)^2 A_a \tag{3}$$

whereas the same calculation using dynamic test efficiency curve parameters follows equation 4 [EN 12975-2; section 6.3]:

$$\dot{Q}_{dyn} = \eta_{0b} K_b(\theta) I_{col} A_a + \eta_{0b} K_d D_{col} A_a - c_1 \left(T_f - T_a\right) A_a - c_2 \left(T_f - T_a\right)^2 A_a - c_5 \frac{dT_f}{dt} A_a \tag{4}$$

Horta et al. (2008) suggested a power correction methodology, applicable to power values determined after Eq.(3), accounting for the collector optical effects, affecting differently the radiation components which reach the absorber surface. According to this methodology, the power value is corrected using the following equation:

$$\dot{Q}_{ss,corr} = \frac{\dot{Q}_{ss}}{1 - f\left(1 - K_{dif,h}\right)} \tag{5}$$

where:

$$f = \frac{D}{G_{col,ref}} \tag{6}$$

is a diffuse radiation fraction to be suggested by the efficiency test laboratory after reference irradiation conditions for the collector test (Horta et al., 2008), and:

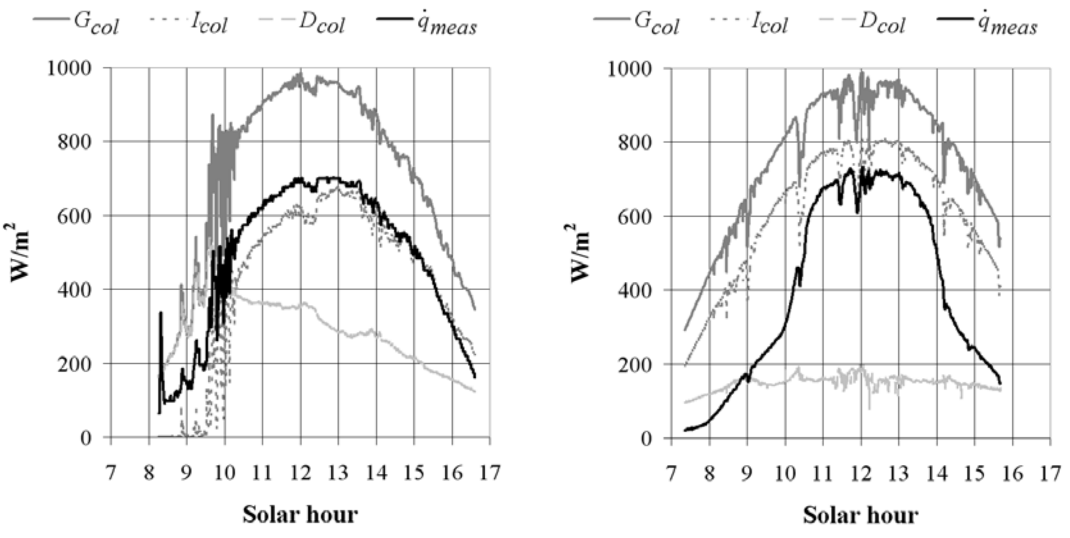
$$K_{dif,h} = \frac{\int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} K(\theta_l, \theta_t) \cos(\theta) \sin(\theta)\, d\theta_t\, d\theta_l}{\int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} \cos(\theta) \sin(\theta)\, d\theta_t\, d\theta_l} \tag{7}$$

is a weighted average hemispherical incidence angle modifier (Carvalho et al, 2007), calculated after the longitudinal and transversal incident angle modifier (IAM) values measured in the steady state efficiency test. Since this correction applies to test results performed according to steady-state test method, the incidence angle modifier is based on hemispherical radiation.

3. Measured sequences used for validation purposes

The comparison of experimental and calculated instantaneous power results, obtained after the different approaches presented in the previous section, is based on instantaneous efficiency measurements for a CPC collector (C = 1.72), as well as on their corresponding steady-state and dynamic efficiency curve parameters. The measurements were made at the Institute for Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart, Germany.

Two measurement periods were chosen, allowing the validation of power calculation methodologies under different radiation conditions. Values of radiation measured on the collector aperture plane (tilt = 48º, azimuth = 5º, latitude = 50º, albedo = 0.2) and measured instantaneous power values are represented in figures 1a) and b) for both periods. In the first measurement period, the collector was positioned on an EW orientation, whereas in the second period the collector was on a NS orientation.



a) b)

Fig.1. Global, Beam and Diffuse irradiance values (G_{col}, I_{col}, D_{col}) incident on collector aperture plane and measured power flux delivered by the solar collector ($\dot{q}_{meas}$) for a) May 2nd and b) May 29th measurements

Considering the use of the power correction methodology proposed by Horta et al. (2008) in power calculations after steady-state efficiency test parameters, average diffuse radiation fractions of 0.3 and 0.25 are estimated for the first and second measurement periods, respectively.

It is important to refer, at this point, that not all data presented in the previous figures would be usable for a steady-state test. Actually, as the name suggests, the steady-state test methodology is based upon a collector heat balance assuming stationary conditions.

Furthermore, it must be cleared that these same measurement periods based the determination of the dynamic efficiency curve parameters used in the calculations to follow.

4. Efficiency test results

The collector was tested according to both steady state test (EN 12975-2;section 6.1) and dynamic test (EN 12975-2; section 6.3) methods. The corresponding characteristic parameters are presented in Table 1.

Table 1. Efficiency curve parameters after steady-state test results

Steady-state test parameters			Dynamic test parameters					
η_0	a_1 [W/ºC.m^2]	a_2 [W/ºC^2.m^2]	η_{0b}	c_1 [W/ºC.m^2]	c_2 [W/ºC^2.m^2]	c_5 [J/kgºC]	$K_d(\theta)$
0.725	3.599	0.007	0.794	3.483	0.010	13647	0.725

Incidence angle modifier (IAM) values obtained, after both test methodologies, for longitudinal and transversal incidences are presented in Table 2.

Table 2. Steady-state and dynamic test results for transversal and longitudinal incidence angle modifier values

Test	θ	10	15	20	25	30	35	40	50	60
Steady	$K_t(\theta)$	0.990	0.999	0.949	0.887	0.632	0.494	0.481	0.482	--
	$K_l(\theta)$	--	--	--	--	--	--	0.957	--	0.853
Dynamic	$K_t(\theta)$	0.966	0.992	0.931	0.840	0.529	0.362	0.328	0.057	--
	$K_l(\theta)$	--	--	--	--	--	--	0.991	--	0.781

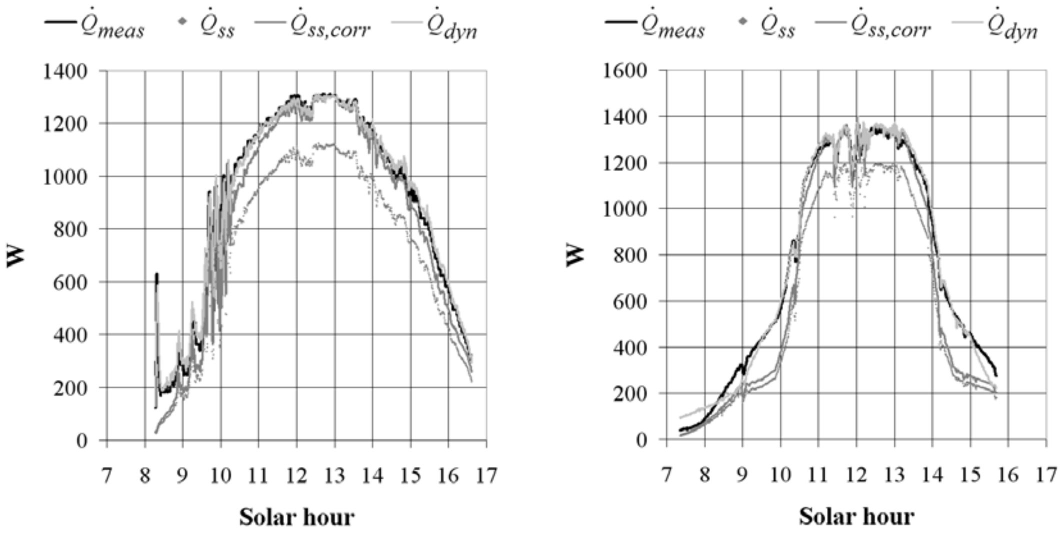
Longitudinal and transversal IAM functions were constructed after 2-points based and linear approximations, respectively (Carvalho et al, 2007). The composed IAM, illustrated in figure 2, follows the McIntire (1983) approximation:

$$K(\theta) \equiv K(\theta_l, \theta_t) \approx K(\theta_l, 0) K(0, \theta_t) \tag{8}$$

The weighted average hemispherical IAM, calculated according to Eq.(7), yields $K_{dif,h}$ =0.529.

5. Power calculations after efficiency test results

Figures 2a) and 2b) illustrate, for both measurement periods, measured ($\dot{Q}_{meas}$) and calculated instantaneous power values, after both steady-state efficiency parameters (uncorrected - $\dot{Q}_{ss}$ - and corrected - $\dot{Q}_{ss,corr}$ - calculations), form Eqs.(3) and (5), and dynamic ($\dot{Q}_{dyn}$) efficiency test parameters, after Eq.(4).



a) b)

Fig.2. Measured ($\dot{Q}_{meas}$) and calculated instantaneous power values, after steady-state test parameters based corrected ($\dot{Q}_{ss,corr}$) or uncorrected ($\dot{Q}_{ss}$) power calculations, or after dynamic test parameters based ($\dot{Q}_{dyn}$) calculations for a) May 2nd and b) May 29th measurement periods

Regarding steady-state test parameters based calculations, integration of measured and calculated power curves in figure 2 yields, for the first measurement period, energy underestimations of 19.7% and 6.5% for uncorrected and corrected calculations, respectively. For the second measurement period, these results change to 21.3% and 10.8% underestimations, respectively.

More than accuracy purposes, which can not be assessed in this case considering that test parameters were produced after these same measured results, the results presented for dynamic test parameters based calculation illustrate the dynamic response of the method.

6. Analysis of results

An assessment of the methodologies presented in section 2 follows directly from the comparison of instantaneous power results presented in section 5 for each of those methodologies.

The results obtained for both measurement periods reveal higher deviation from measured value, for the steady-state based calculation, whenever steep variations on irradiation conditions occur, as clearly illustrated in fig.2b) for the periods between 09.00 - 10.30 and 14.00 - 15.30. This result is in line with the base assumptions of such methodology which does not account with transient conditions, as in the dynamic methodology accounting a time dependent temperature variation term.

Considering the use of steady-state parameters, by far the most commonly available for marketed collectors, these results also clear the advantage of using the power correction methodology proposed by Horta et al. (2008). In fact, for both measurement periods, the results obtained after this methodology present closer results to measured values throughout the entire set of measurements. Lacking, in the same way, a dynamic response to steepest irradiation variations (which the power correction methodology did not claimed to correct), such power correction presents particularly good results in mid-day periods, where milder variations where observed.

7. Conclusions

Test sequences of a CPC type collector were obtained allowing the application of two test methodologies, presently available for characterization of the efficiency of glazed collectors: i) steady state test methodology [EN 12975-2: section 6.1] and ii) quasi-dynamic test methodology [EN 12975-2: section 6.3], based on different model approaches for a solar collector and, consequently, imposing different algorithms for calculating the power (and energy) delivered by solar thermal collectors.

The different algorithms were presented, including the application of an algorithm for correction of power/energy results to steady state results as proposed by Horta et al. (2008). Application of these algorithms to two days of measured data allowed for a comparison of the results obtained with these different methodologies.

The results obtained allow the following conclusions:

- calculations based in steady-state test parameters lack dynamic response, leading to increased power underestimations under steep variation of irradiation conditions;
- calculations based in dynamic test parameters, accounting for transient conditions after adoption of a time dependent temperature variation term, reveal a closer response under such conditions;
- considering the use of steady-state parameters, by far the most commonly available for marketed collectors, the use of the power correction methodology proposed by Horta et al. (2008) leads to more accurate results, revealing better results throughout the entire set of measurements and particularly good results under irradiation conditions closer to stationarity (milder variations, as in mid-day periods).

Furthermore, and regarding the algorithm for correction of power/energy results to steady state results proposed by Horta et al. (2008), these results validate its application against measured results of independent test of a general product. The results obtained recommend its adoption in the different software tools making use of steady-state efficiency test results.

Nomenclature

A_a	collector aperture area, (m^2)
a_1	global heat loss coefficient, ($W/m^2.K$)
a_2	temperature dependent heat loss coefficient, ($W/m^2.K^2$)
C	concentration ratio
c_1	global heat loss coefficient, ($W/m^2.K$)
c_2	temperature dependent heat loss coefficient, ($W/m^2.K^2$)
c_5	dynamic response coefficient
I	beam radiation, (W/m^2)
I_{col}	beam radiation incident on the collector aperture plane, (W/m^2)
D	diffuse radiation incident on the horizontal plane, (W/m^2)
D_{col}	diffuse radiation incident on the collector aperture plane, (W/m^2)
f	diffuse radiation fraction

$\boldsymbol{G}$	global irradiance incident on the horizontal plane, (W/m^2)
$\boldsymbol{G_{col}}$	global irradiance incident on the collector aperture plane, (W/m^2)
$\boldsymbol{G_{col,ref}}$	global irradiance incident on the collector aperture plane under collector test reference conditions, (W/m^2)
$\boldsymbol{K(\theta)}$	beam radiation incidence angle modifier (steady-state test)
$\boldsymbol{K_b(\theta)}$	beam radiation incidence angle modifier (dynamic test)
$\boldsymbol{K_d}$	diffuse radiation incidence angle modifier (dynamic test)
$\boldsymbol{K_{dif,h}}$	hemispherical diffuse radiation weighted average incidence angle modifier
$\dot{q}$	power flux, (W/m^2)
$\dot{Q}$	power, (W)
$\dot{q}_{meas}$	measured power flux, (W/m^2)
$\dot{Q}_{meas}$	measured power, (W)
$\dot{Q}_{dyn}$	power calculated after dynamic efficiency curve parameters, (W)
$\dot{Q}_{ss}$	power calculated after steady-state efficiency curve parameters, (W)
$\dot{Q}_{ss,corr}$	power calc. after steady-state effic. params. and power correction methodology, (W)
$\boldsymbol{R_g}$	ground reflected radiation, (W/m^2)
$\boldsymbol{T_a}$	air temperature, (ºC)
$\boldsymbol{T_f}$	average heat transfer fluid temperature, (ºC)
$\boldsymbol{\beta}$	collector tilt angle, (º)
$\boldsymbol{\eta}$	collector instantaneous efficiency
$\boldsymbol{\eta_0}$	collector optical efficiency
$\boldsymbol{\eta_{0b}}$	collector beam optical efficiency
$\boldsymbol{\theta}$	incidence angle, (º)
$\boldsymbol{\theta_l}$, ($\boldsymbol{\theta_t}$)	incidence angle projection in the longitudinal (transversal) plane (º)
$\boldsymbol{\theta_z}$	incidence angle on the horizontal plane (º)
$\boldsymbol{\rho_g}$	ground reflectivity (albedo)

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