Solar thermal collectors under transient conditions: optical and thermal characterization based on the quasi-dynamic model

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Abstract

Efficiency tests have been performed to solar collectors since the 70’s, when the first main standard, ASHRAE 93:1977, was released. Currently, the most important standard in Europe is the EN 12975:2006, which is based on the ISO 9806:1994 standard. The EN 12975:2006 standard is applied in all the major laboratories testing solar collectors and is the reference for the Solar Keymark network. In these three standards the efficiency is determined under stationary and clear-sky conditions. Besides the steady-state method, the EN 12975 standard also allows the application of a quasi-dynamic method performed outdoors in natural conditions with variable radiation intensity and ambient temperature. The Solar Energy Laboratory (LES) in Lisbon is a European-Union accredited laboratory that performs the quasi-state efficiency test for collector certification. The main purpose of this work is to implement the quasi-dynamic test method according to the EN 12975-2, clause 6.3, at the LES. The impact on the number of days available for the tests was investigated by analyzing meteorological data series acquired in the laboratory since 2007. It was concluded that roughly twice the collectors could be tested per year if this new method were used, with the greatest impact in the winter months, when almost no collectors can by tested by the steady-state method. Both the steady-state and the quasi-dynamic methods were applied in over 40 days of testing to five collectors: two flat plate collectors, one evacuated tube collector with a back reflector and direct flow circulation, one evacuated tube collector with heat pipes, and a CPC (compound parabolic concentrator) collector. The results were compared and a good agreement between the steady-state and the quasi-dynamic test results was observed. Some issues concerning the incidence angle modifiers and the effective thermal capacity of the collectors were analyzed in detail, which resulted in the identification of some limitations of the model and tests, for which solutions were proposed.

Keywords: Solar collector testing; Quasi-dynamic model; Steady-state model; EN 12975

1. Introduction

Tests on performance and quality of solar collectors have a fairly long history. The current European standards were developed on the basis of the ISO and ASHRAE standards created before 1990. In the most common test methods recommended by ISO 9806-1.3 (ISO 1994), EN 12975-2 (CEN, 2006) and ASHRAE 93 (ANSI/ASHRAE, 2003) the collector thermal efficiency is determined under stationary conditions. The EN 12975-2 standard also allows testing according to the quasi-dynamic method (clause 6.3), performed under natural conditions (outdoors) with variable radiation and ambient temperature.

In the past years, this method has been applied to several types of solar collectors, namely, flat plate, CPCs (compound parabolic concentrators) and ETCs (evacuated tubular collectors) (Perers 1997, Horta et al. 2008, Zambolin & Del Col 2010). The concentrating collectors are also mentioned in the ASHRAE 93-77, ISO 9806-1 and EN 12975-2 standards but no specific test methods have been developed within these standards. However the quasi-dynamic test was applied to a parabolic trough with good results (Fischer et al. 2006).

The accredited testing laboratories use these procedures and characteristic equations for determining the thermal performance of solar collectors. These results are mandatory for certification of these products.

The Solar Energy Laboratory (LES) is, since 2002, a European-Union accredited laboratory according to the quality management standard EN ISO/IEC 17025. At this point, the laboratory is accredited for testing solar collectors in accordance with EN 12975-1.2:2006. The accreditation for testing the thermal performance of collectors only refer to clause 6.1 of the EN 12975-2 standard: Glazed solar collectors under steady-state conditions (including pressure drop). One of the objectives of this work is to get this accreditation extended to include clause 6.3 of the standard: Glazed and unglazed solar collectors under quasi-dynamic conditions.

The understanding of the transient behavior of a solar collector is important to know how it will perform during the initial phase of heating, how temperature will vary in days with intermittent clouds, when auxiliary heaters will be needed and is also important to study dynamic systems that have solar collectors as components, such as solar cooling systems. These concerns have led to the development of many models since the late 70s until now.

Some of these models aim to simulate the behavior of a specific collector and are usually based on the thermophysical properties of materials that constitute the collector and on energy transfer phenomena, such as radiation, convection and conduction, using heat transmission coefficients and correlations available in the literature. These models give good insight into the constructive aspects that have impact on the performance of the collector (de Ron 1980, Saito et al. 1984, Zhao et al. 1988, Cadafalch 2009, Rodríguez-Hidalgo et al. 2011).
Other models are intended to serve as a basis for developing experimental test methods for identification of the characteristic parameters of the collector through non-intrusive means, i.e., no instrumentation is placed inside the collector like measuring the temperature of the absorber plate, the glazing or the isolation (Emery & Rogers 1984, Kamminga 1985, Wang & Isom 1987, Muschaweck & Spirk 1993, Isakson & Eriksson 1994, Perers 1993 and 1997, Fischer & Müller-Steinhagen 2009). The Perers model is the basis of the quasi-dynamic model owing to its simplicity and ease of use.

1.1. Available testing days

The quasi-dynamic method has the largest annual number of days available for testing when compared with the steady-state method, and less intervention from the operator is required. These factors are, in the testing laboratory’s point of view, the main arguments for the implementation of the quasi-dynamic method. The LES (38 ° 46’ N, 9 ° 11’ W) has a data acquisition system that records continuously all the major meteorological variables (radiation, ambient temperature, etc.). These data are available, with few flaws, since the year 2007 with acquisition times ranging from 1 to 5 min. These data, made it possible to analyze the potential impact that testing by the quasi-dynamic method would have on the number of collectors that would be possible to test annually. The methodology used in this analysis differs from the ones mentioned in the literature (Emery & Rogers 1984, Kratzenberg et al. 2002, Rojas et al. 2008) and applies specifically to the particularities of thermal performance tests in the LES. In this laboratory, for each test performed with the steady-state method it takes about 3 hours to reach the desired temperature, stabilize the circuit and perform the test. In a clear-sky day only two temperature levels are usually tested. When analyzing the data, each day was identified as having: a) zero b) one (1/2 SS day) or c) two (SS day) 3 hour periods in which radiation was stable.

A quasi-dynamic test day (QD day) was defined as all the days that allow steady-state tests and those in which there is variation in solar radiation. Days with daily irradiation on the tilted surface of less than 10 MJ were rejected even if in some cases they could have allowed the quasi-dynamic test to be performed.

It was possible to conclude that the number of days available to perform the quasi-dynamic test is about twice the number of days suitable for testing with the steady-state method. In addition, the analysis showed that the quasi-dynamic test can be run in more than 75% of the days of the year.

A complete collector test according to the steady-state method normally takes four days: three days to determine the heat capacity and the efficiency at five temperature levels, and another day for the characterization of the incidence angle modifier. The EN 12975-2 standard states that the test only requires four temperature levels, but the procedure adopted in the LES involves five different inlet temperatures. In the case of the quasi-dynamic method, the time interval for a full test is five days, divided into four levels of temperature with one level per day and another day with a different collector tilt angle for the determination of the longitudinal dependence of the incidence angle modifier. On the basis of these definitions and taking into account the number of days that enable each test type, it is possible to conclude that the test ability of the LES would roughly double if the quasi-dynamic test method were implemented.

The data can also be interpreted from the perspective of distribution of tests over the months of the year (Table 1).

| Table 1 - Day classification and total number of collectors to be tested each month |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Jan | Feb | Mar | Apr | Mai | Jun | Jul | Aug | Set | Oct | Nov | Dec |
| Total days | 28 | 26 | 31 | 30 | 31 | 29 | 30 | 31 | 29 | 28 | 26 |
| QD days | 15 | 17 | 27 | 27 | 28 | 28 | 29 | 30 | 28 | 26 | 19 | 14 |
| SS days | 2 | 5 | 7 | 6 | 7 | 10 | 16 | 18 | 10 | 7 | 7 | 1 |
| 1/2 SS days | 3 | 1 | 3 | 4 | 3 | 5 | 5 | 5 | 5 | 2 | 1 | 6 |
| Collectors QD | 3 | 3 | 5 | 5 | 6 | 6 | 6 | 6 | 5 | 4 | 3 |
| Collectors SS | 1 | 1 | 2 | 2 | 2 | 3 | 5 | 5 | 3 | 2 | 2 | 1 |

As expected, in the winter months the number of days in which the tests can be performed is much smaller than in the summer months, but even half of December and January days are suitable for quasi-dynamic testing, in contrast with steady-state testing, which is nearly impossible to perform during these months.
months. From March to October, the quasi-dynamic test can be conducted in more than 85% of days.

Regarding the number of collectors (Table 1), the analysis confirmed that by applying the steady-state method only one collector could be tested in December, January and February and that this value triples with the quasi-dynamic method. Only in July and August the number of collectors that could be tested by the two methods is similar.

1.2. The steady-state method

The steady-state method, which is based on the steady-state model, implies that all important variables for the thermal characterization of a collector must remain constant throughout the test period. The solar radiation incident on the collector, the ambient temperature, the temperature of the heat transfer fluid at the entrance and the mass flow rate should be within certain limits defined by EN 12975-2:2006 clause 6.1 (see Table 2). The percentage of diffuse radiation and the wind speed over the collector are also limited.

The useful power output of a solar collector according to the heat balance equation of the steady-state model at a nearly normal incidence of solar radiation is given by equation (1).

\[
\frac{\dot{Q}}{A} = \eta_0 G - a_1(t_m - t_d) - a_2(t_m - t_d)^2
\]

Where \( \eta_0 \) is the collector efficiency for the global radiation incident in the normal direction when there are no losses (optical efficiency), \( a_1 \) and \( a_2 \) describe the heat loss and the dependence of heat loss on temperature and \( t_m \) is the average temperature of the fluid inside the collector.

The efficiency curve is determined with normal incidence radiation in the collector. The use of sun-tracking devices allows testing under these conditions, regardless of the position of the sun (time of day).

There are also experimental procedures to obtain the angular dependence of the optical performance, called the incidence angle modifier (IAM) \( K_\theta(\theta) \), and the effective thermal capacity, \( c_{de} \). The most complete heat balance equation that can be written on the basis of the steady-state method is:

\[
\frac{\dot{Q}}{A} = \eta_0 K_\theta(\theta) G - a_1(t_m - t_d) - a_2(t_m - t_d)^2 - c_{eff} \frac{dt_m}{dt}
\]

In this model there is no correction term for the diffuse radiation, which is usually required in simulation programs for the long-term behavior of collectors. This is due to the fact that this is a clear-sky model (low percentage of diffuse radiation).

1.3. The quasi-dynamic method

The quasi-dynamic model derives from the steady-state model by adding some correction terms that allow a more detailed description of the collector that include its transient performance. Solar radiation is now considered in its two components - direct and diffuse - with corresponding IAMs. The dependence on wind speed is modeled by two corrective terms, the effect of the wind on the optical performance and its influence on heat losses. Finally, the last correction describes the dependence of losses due to radiation of long wavelength incident on the collector. The net power provided by a collector, according to the quasi-dynamic model, is given by equation (3).

\[
\dot{Q} = F'(\alpha) e \eta_0 b G_b + F'\alpha e \eta_0 a d G_a - c_{33} t G
\]

\[
-c_1(t_m - t_d) - c_2(t_m - t_d)^2 - c_3 t(t_m - t_d)
\]

\[
+ c_4(E_L - \sigma T_a^4) - c_5 \frac{dt_m}{dt}
\]

The incidence angle \( \theta \) is defined as the angle between the direction of sunlight and the normal direction of the collector. To account for the change in the collector’s thermal performance due to the incidence angle, the IAM is introduced, defined as the fraction between the optical efficiency for a given angle and the efficiency at normal incidence.

\[
K_\theta(\theta) = \frac{\eta_\theta(\theta)}{\eta_\theta(\theta = 0)}
\]

In the steady-state model, equation (2), the IAM is multiplied by the global radiation and the model is only valid when the fraction of diffuse radiation is less than 30%. In the quasi-dynamic model, equation (3), the decomposition of radiation into its direct and diffuse components allows the definition of two distinct IAMs, one for the diffuse radiation \( K_\theta(\theta) \) modeled as a constant, and other for the direct radiation \( K_\theta(\theta) \) modeled as a function of incidence angle.

According to their behavior in relation to the angle of incidence, it is possible to distinguish three types of collectors: isotropic, biaxial and multi-axial.

Fig. 1 – Transversal and longitudinal directions and plans of the collector (NEGST, 2007)

In Fig. 1 a system of coordinates is shown, formed by two directions in the plane of the collector and by its normal direction. The longitudinal axis is in the north-south direction and the transversal axis in the east-west direction. The longitudinal and transversal planes are defined by the corresponding direction and are perpendicular to the collector. The longitudinal angle of incidence \( \theta_1 \) is the angle between the direction normal to the collector and the projection of the sun’s position into the longitudinal plane. In the same way, the transversal incidence angle \( \theta_2 \) is obtained by the projection into the transversal plane.

For an isotropic collector, the efficiency is independent of the direction of the incident radiation,
and this is what happens in most flat plate collectors. Thus, the behavior of the collector can be modeled by an IAM that only depends on the angle of incidence 
\[ K_0 = f(\theta) \]

Bi-axial collectors respond differently to radiation parallel to the longitudinal axis or parallel to the transversal axis. However, they have symmetry with respect to transverse and longitudinal planes. The most common examples of bi-axial collectors are the evacuated tubular collectors, CPC collectors and parabolic trough collectors. The modeling is made through an IAM that is both function of the longitudinal and of the transversal incidence angles 
\[ K_0 = f(\theta_L, \theta_T) \]

For the multi-axial collectors there is no symmetry in the longitudinal, transversal, or in both, directions. In this case, the IAM function has to take into account all relevant directions for the angle of incidence.

The simplest model for the IAM, which applies to collectors with isotropic behavior, is given by equation (5) with the parameter \( b_0 \) adjusted to the experimental data.

\[ K_0(\theta) = 1 - b_0 \left( \frac{1}{\cos \theta} - 1 \right) \]  

However, this model does not apply to all isotropic collectors, for example to flat plate collectors with transparent insulation (TIM). Thus, the methodology generally applied to all types of collectors is to fill a table with experimental points for various angles and interpolate the desired value through the adjacent values. The number of points required depends on the complexity of the IAM.

For collectors with bi-axial geometry the IAM can be split into two components, longitudinal and transversal, being valid the following approach (McIntire 1982).

\[ K_0(\theta_L, \theta_T) = K_0(\theta_L, \theta_T = 0), K_0(\theta_L = 0, \theta_T) \]  

It is also possible to consider that equation (5) is valid for one direction and to characterize the other direction through the discrete function with the angle intervals. This approach also extends to collectors with multi-axial angle modifiers.

1.4. Testing conditions

The test conditions and the permitted deviations from the average for the variables measured during the quasi-dynamic test are presented in Table 2. For comparison, the values for the steady-state test method are also presented.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Steady-state</th>
<th>Quasi-dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global radiation ( G ) [W/m²]</td>
<td>&gt;700</td>
<td>± 50</td>
</tr>
<tr>
<td>Incidence angle ( \theta ) [°]</td>
<td>&lt;20</td>
<td>-</td>
</tr>
<tr>
<td>Diffuse fraction ( Q_d / Q ) [%]</td>
<td>&lt;30</td>
<td>-</td>
</tr>
<tr>
<td>Ambient temperature ( T_o ) [K]</td>
<td>-</td>
<td>±1.5</td>
</tr>
<tr>
<td>Wind speed ( u ) [m/s]</td>
<td>2&lt;u&lt;4</td>
<td>1&lt;u&lt;4</td>
</tr>
<tr>
<td>Inlet temperature ( T_i ) [K]</td>
<td>-</td>
<td>±0.1</td>
</tr>
<tr>
<td>Mass flow rate ( m ) [kg/s/m²]</td>
<td>0.02</td>
<td>±1%</td>
</tr>
</tbody>
</table>

The boundary indicated for the global radiation is just for the thermal efficiency test, because on the IAM test this limit is 300 W/m². An incidence angle of 20 ° is acceptable only for flat plate collectors, for other types this value may need to be much smaller. The variation of flow rate between different tests is also limited to be less than 10% in the two test methods.

The constraints of the steady-state method are often satisfied during the quasi-dynamic test so one can select ranges of data and analyze them according to the steady-state method. A complete set of test data will take about four to five days, although in reality the total number of days always depends on the weather conditions, which must ensure enough variability covering the normal operating conditions of the collector and ensure the independence of the calculated parameters.

Data sets must be obtained for at least four fluid temperatures at the entrance at regular intervals over the operating range of the collector. Each test sequence must extend for at least 3 hours. The lowest temperature should be chosen so that the average temperature in the collector is within ± 3 K of the ambient temperature near the solar noon, for a correct determination of the optical performance of the collector. This sequence must be performed on a clear day and should include values of the angle of incidence above 60 ° and also values for which the difference in the IAM for a normal incidence does not exceed 2 %.

At least one of the test sequences should be performed under varying sky conditions, with periods of clouds and clear sky for the correct determination of the thermal capacity. In this test sequence, the \( \Delta T_{in} / \Delta t \) value must be greater than 0.005 K/s. It may be at a high inlet temperature or near ambient temperature.

2. Experimental setup

The quasi-dynamic test was implemented on the same hydraulic circuit and test rig as those used for testing according to the steady-state method. In this way it will be possible to optimize the use of this circuit to perform steady-state or quasi-dynamic tests in alternation, according to weather conditions. Furthermore, this setup made simpler to make a comparison between the two methods when applied to the same collector.

The circuit allows the testing of two collectors simultaneously at the same level of inlet temperature. The fluid returning from the collectors is initially cooled in a plate heat exchanger at a temperature of 5 °C below the test temperature set point. This process is managed by a PID controller which operates a three-way valve that enables the regulation of the amount of water that goes to the cooling tank. The tank’s temperature is also controlled, typically at 15 °C below the set point, by the introduction or retention of mains water. After being cooled, the test fluid is heated to the test temperature, in a boiler with 20 l capacity and 7,5 kW power. A fraction of the fluid is fed back to achieve a good homogenization. The circuit is pressurized, which allows operating at temperatures above 100 °C. There is also a unit of filtration and water treatment (with salt) at the circuit entrance.

The collectors are installed in a test bench that enables the collector to be tilted at an angle between ± 60 °. The elevation of the collectors to a tilt angle from approximately 75 ° to 15 °. The airflow over the collectors’ surface is guaranteed by the use of centrifugal fans with frequency regulation.

The temperature sensors are of the PT100 type and maintain a stable temperature sensor is installed inside a radiation shield with natural ventilation. Their standard uncertainties are less than 0.06 °C. The flow meters are of the electromagnetic type with calibration standard
uncertainties below 0.01 l/min. Cup anemometers were used, with an associated standard uncertainty of 0.1 m/s. The pyranometers used have a maximum standard uncertainty of 1.5 %.

For measuring the direct radiation a pyrhemeter with a tracking system was used, with a standard uncertainty of 1.1 %. To measure the long wavelength radiation a pirgeometer was installed. Although its calibration is out-of-date, the values of several tests obtained with this equipment are in line with what the literature predicts and it was considered that its use was acceptable for this work.

A software program has been developed for managing the acquisition and pre-processing of data. For each test day, the user must enter data such as tilt and azimuth of the collector, the readings’ frequency (typically 3 s) and the duration of the intervals for which data are compressed into a mean value (typically 5 min).

3. Data treatment

The identification of collector parameters is done by adjusting the coefficients of the model that best reproduces the experimental results, i. e., to minimize the error between the collector power output calculated by the model and that determined experimentally. Over the steady-state mode, written as an efficiency function, the quasi-dynamic method has the advantage that it can be used directly in a simulation program to calculate the power supplied and is also more accurate for higher values of the reduced temperature (Perers 1993, Fischer et al. 2004).

The most widely used mathematical tool to solve this problem is the multiple linear regression (MLR) (Perers 1993, Fischer et al. 2006) also referred to in the EN 12975-2 standard, although there have been good results also reported with the dynamic parameters identification approach (Fischer et al. 2006, Muschaweck & Spirk 1993). Linear just means that the equation is written as a sum of functions weighted by the parameters to be determined. These functions can be highly nonlinear.

For unglazed collectors all the model parameters are required. For other collector types, the parameters $c_3$, $c_4$ and $c_5$ are optional and their use is defined by the criterion (T-ratio) that the ratio between the value of the parameter and its standard deviation resulting from the regression be greater than 2.

The approaches to determine the IAM can be more or less complex according to the collector type. When the collector can be described by equation (5) the model continues to be a linear combination of functions and the value of $b_0$ is determined during the regression. When there is no elementary function to describe the angle modifier, the adopted treatment was proposed by Perers (1997) and makes use of so-called "dummy variables" (Weisberg 2005). The term of the equation (3) relative to the direct radiation angle modifier $K_{al}(	heta)$ must be separated in different classes of angles, i. e., it becomes a value that represents the angle modifier for a given interval of $\theta$ (equation (7)). In most general cases, in which collectors have a biaxial symmetry, one defines classes for transversal $\theta_{ij}$ and longitudinal $\theta_{ij}$ angles. They may be, for example, every 5 °.

\[
F'(\tau_a)_{en} K_{al}(\theta_{ij}) K_{al}(\theta_{ij}) G_b \rightarrow \sum_{j=1}^{max} K_{al} b_{ij} \sum_{i=1}^{max} K_{al} b_{ij} G_b
\]

(7)

For some experimental point, $\theta_{ij}$ and $\theta_{ij}$ take the value of 1 in the class corresponding to the measured angles and 0 in the remaining classes. By definition we also have $K_{al} = K_{al} = 1$ because they represent a normal incidence.

This method can be applied equally to a discretization of the dependence of the collector heat loss on temperature (Perers 1997) although it is generally considered that the linear and quadratic terms are sufficiently representative.

3.1. Multiple Linear Regression (MLR)

The resolution of the regression is simultaneous with the calculation of uncertainties (Mathioulakis et al. 1999, Müller-Schöll & Frei 2000, Sabatelli et al. 2002, Kratzenberg et al. 2006). The problem that arises is how to adjust a set of N experimental points $(\bar{x}_j, y_j)$ to a particular model that can be written as a linear combination of M arbitrary functions $X_k(\bar{x})$.

\[
y(\bar{x}) = \sum_{k=1}^{M} a_k X_k(\bar{x})
\]

(8)

The objective of the adjustment is to minimize the merit function $\chi^2$.

\[
\chi^2 = \sum_{i=1}^{N} \frac{y_i - \sum_{k=1}^{M} a_k X_k(\bar{x}_i)}{u_i}
\]

(9)

Where $u_i$ is the uncertainty of the experimental point $i$. When its value is unknown, it is considered that the uncertainty is constant and $u_i = 1$ (the least squares method). In a real case the uncertainty varies between experimental points and the value of $u_i$ is not constant and this method becomes the weighted least squares regression. The solution can be found in literature (Press et al. 1994).

In the case of parameter identification for the test models of solar collectors, the $u_i$ uncertainties are unknown and depend themselves on the parameters of the fit. Explicitly, $u_i^2$ is the variance of the difference $y_i - \sum_{k=1}^{M} a_k X_k(\bar{x}_i)$ and, by the application of the uncertainty propagation law, equation (13) is obtained.

\[
u_i^2 = u^2(y_i) + \sum_{k=1}^{M} a_k^2 u^2(X_k(\bar{x}_i))
\]

(10)

Thus, equation (9) is nonlinear and identification of parameters has to be done using methods such as Levenberg-Marquardt. However, in accordance with Annex K of the EN 12975-2 standard, it is acceptable to use the method of least squares to obtain a first set of parameters $a_k$ from which one calculates the uncertainties $u_i$ and then a new set of parameters, which should not differ much from the previous ones.

3.2. How to compare steady-state and quasi-dynamic models

The comparison between the parameters obtained by the quasi-dynamic test and the steady-state test, in accordance with clause 6.3.4.8.4 of the EN 12975-2 standard should be made through the collectors’ power curves as a function of the temperature difference between ambient and average fluid temperature. The power
curve should be parameterized by a global radiation of 1000 W/m². The EN 12976-2 standard also states that the following parameters should be considered: a fraction of 15% of diffuse radiation; the stationary operation (da/dt=0); and to assign a value of 15 ° to the incidence angle.

This angle is imposed to adjust the power curve at conditions near solar noon and comes from a context in which the steady-state test was performed to a static collector facing south without tracking the sun, the experimental points were obtained within the -20°<θ<20° interval or, historically, within the -30°<θ<30° interval. When the test is conducted with solar tracking, as it is in the case of the LES, all the experimental points are acquired for angles of incidence that are much lower. According to the procedure used at the LES, the orientation of the collector is made at intervals of 10 min which means that the maximum angle of incidence is 2.5 °. Thus, it makes no sense to use the value of 15 ° in these conditions and the value 0 ° was used in this study considering the normal incidence.

When the parameters ca, cb and c0 are significant and have positive values they should be included in the model. For comparing the power curves the values of u=3 m/s and (E1·oT)²=100 W/m² are taken. The value of 3 m/s imposed by the EN 12976-2 standard does not correspond to the test situation, as the air speed measured at the top of the collector is less than 3 m/s, even if this value is reached at the collector midpoint. As the steady-state test is performed under the same conditions as the quasi-dynamic test, the value adopted for u was the average air speed measured during the steady-state test. Equation (3) is then:

\[ Q = \frac{F'(\tau a)_{en} K_{gb}(0) \times 850 + F'(\tau a)_{en} K_{gd} \times 150 - c_d u L_s \times 1000 \times (c_1 + c_2 \cdot \mu G) (m - d - t)}{c_d (t_m - t_d)^2 - c_d \times 100} \]  

(11)

In most glazed collectors, parameters c4 and c0 are neglected, but they are retained in the following equations to represent the general case. By comparing equations (2) and (3) for a normal incidence of solar radiation, we can write the optical efficiency, the parameters a1 and a2 and the thermal capacity as:

\[ \eta_0 = \frac{F'(\tau a)_{en} (G_b + K_{gd} G_d) - c_d u G + c_4 (E_L - \sigma T_d^4)}{G} \]  

(12)

\[ a_1 = (c_1 + c_3 \cdot U) \]  

(13)

In the same way one can obtain the transformation of the IAM:

\[ K_{gb}(\theta) = \frac{F'(\tau a)_{en} K_{gb}(\theta) + K_{gd} G_d - c_d u G + c_4 (E_L - \sigma T_d^4)}{\eta_0 G} \]  

(16)

4. Results

In this study, five collectors were tested by the steady-state and quasi-dynamic methods, over 43 days, from June to September. Different types of collectors bring different challenges to testing and data analysis. To cover these aspects as thoroughly as possible, two flat plate collectors (FPC 1 and FPC 2), an evacuated tubular collector with direct flow and a back reflector (ETC DF), an evacuated tubular collector with heat pipes (ETC HP) and a CPC type collector were tested.

Table 3 and Table 4 show the values obtained for the significant parameters of the quasi-dynamic model and its uncertainties. The parameter c0 showed no significance in all cases. For the CPC collector two results are presented -- referred to as (1) and (2) -- differing in the inclusion or exclusion of the parameter c0. See discussion of results in section 5.

![Fig. 2 – FPC 1 collector's power curve (G=1000 W/m²)](image)

The comparison between the results of the two test methods was performed according to the methodology described in section (3). The parameters obtained are summarized in Table 5. The values of the IAM for the

<table>
<thead>
<tr>
<th>Collector</th>
<th>b0 long. [±]</th>
<th>10—15 [±]</th>
<th>20—25 [±]</th>
<th>30—35 [±]</th>
<th>40—45 [±]</th>
<th>50—55 [±]</th>
<th>60—65 [±]</th>
<th>65—70 [±]</th>
<th>70—75 [±]</th>
<th>75—80 [±]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC 1</td>
<td>0.215 ± N.A.</td>
<td>1.01 ± 0.01</td>
<td>1.03 ± 0.01</td>
<td>1.04 ± 0.01</td>
<td>1.02 ± 0.01</td>
<td>1.04 ± 0.01</td>
<td>1.19 ± 0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FPC 2</td>
<td>0.175 ± N.A.</td>
<td>1.01 ± 0.01</td>
<td>1.09 ± 0.01</td>
<td>1.22 ± 0.02</td>
<td>1.43 ± 0.02</td>
<td>1.57 ± 0.03</td>
<td>1.58 ± 0.05</td>
<td>1.42 ± 0.07</td>
<td>1.60 ± 0.10</td>
<td>1.39 ± 0.20</td>
</tr>
<tr>
<td>ETC DF</td>
<td>0.439 ± N.A.</td>
<td>0.98 ± 0.01</td>
<td>0.96 ± 0.01</td>
<td>0.97 ± 0.01</td>
<td>0.91 ± 0.01</td>
<td>0.79 ± 0.01</td>
<td>0.63 ± 0.02</td>
<td>0.52 ± 0.03</td>
<td>0.49 ± 0.05</td>
<td>0.53 ± 0.08</td>
</tr>
<tr>
<td>ETC HP</td>
<td>0.267 ± N.A.</td>
<td>0.98 ± 0.01</td>
<td>0.95 ± 0.01</td>
<td>0.95 ± 0.01</td>
<td>0.87 ± 0.01</td>
<td>0.73 ± 0.01</td>
<td>0.51 ± 0.02</td>
<td>0.33 ± 0.03</td>
<td>0.18 ± 0.04</td>
<td>0.04 ± 0.07</td>
</tr>
</tbody>
</table>

Table 3 – Quasi-dynamic model parameters for the collectors tested and their uncertainties

Table 4 – Direct radiation IAM for the ETCs and CPC collectors tested and their uncertainties (just some intervals)
global radiation are compared in Table 6, in which the angle values considered are the values required by the EN 12975-2 standard, i.e., 50° to the isotropic collectors and for the longitudinal direction of biaxial collectors and 20, 40 and 60° for the transversal direction.

According to the EN 12975 standard, the test results are often expressed by an output power curve of one collector unit, parameterized by a value of 1000 W/m² for the radiation. Fig. 2 is an example of the curves obtained by applying the test parameters of the steady-state and quasi-dynamic models. Curves are also drawn to one standard deviation of the power curve of the steady-state test taking into account the uncertainties of the experimental instrumentation and statistics.

5. Discussion

5.1. The quasi-dynamic test method

The quality of experimental data of the five collectors tested according to the quasi-dynamic method has been established to the extent that it allowed an unambiguous identification of the collector's parameters. The model allowed a very close representation of the actual collectors' behavior, both in clear-sky conditions or in conditions of great variability of solar radiation. Figure (3) represents the worst case (ETC HP collector). The standard error of the estimated power is given in the table (7).

In all cases, the parameter \( c_{\text{eff}} \), which represents a decrease in optical efficiency with air speed, had meaning.

<table>
<thead>
<tr>
<th>Collector</th>
<th>Method</th>
<th>( \eta_0 ) [-]</th>
<th>( a_1 ) [W/(m²K)]</th>
<th>( a_2 ) [W/(m²K)]</th>
<th>( C_{\text{eff}} ) [kJ/(m²K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC 1</td>
<td>Steady-state</td>
<td>0.734 ± 0.002</td>
<td>4.6 ± 0.2</td>
<td>0.008 ± 0.003</td>
<td>8.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.720 ± 0.002</td>
<td>3.9 ± 0.2</td>
<td>0.015 ± 0.002</td>
<td>9.6 ± 0.3</td>
</tr>
<tr>
<td>FPC 2</td>
<td>Steady-state</td>
<td>0.719 ± 0.003</td>
<td>3.8 ± 0.2</td>
<td>0.012 ± 0.003</td>
<td>6.6 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.715 ± 0.001</td>
<td>3.9 ± 0.1</td>
<td>0.012 ± 0.001</td>
<td>7.8 ± 0.1</td>
</tr>
<tr>
<td>ETC DF</td>
<td>Steady-state</td>
<td>0.625 ± 0.003</td>
<td>1.1 ± 0.2</td>
<td>0.003 ± 0.002</td>
<td>37.6 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.618 ± 0.003</td>
<td>0.9 ± 0.1</td>
<td>0.006 ± 0.002</td>
<td>30.9 ± 0.6</td>
</tr>
<tr>
<td>ETC HP</td>
<td>Steady-state</td>
<td>0.669 ± 0.002</td>
<td>1.8 ± 0.2</td>
<td>0.015 ± 0.002</td>
<td>101.2 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.673 ± 0.001</td>
<td>2.8 ± 0.4</td>
<td>0.003 ± 0.005</td>
<td>65.2 ± 2.4</td>
</tr>
<tr>
<td>CPC</td>
<td>Steady-state</td>
<td>0.650 ± 0.002</td>
<td>3.5 ± 0.2</td>
<td>0.010 ± 0.003</td>
<td>7.5 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.651 ± 0.007</td>
<td>3.9 ± 0.1</td>
<td>0.008 ± 0.002</td>
<td>8.7 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.651 ± 0.007</td>
<td>3.4 ± 0.1</td>
<td>0.013 ± 0.002</td>
<td>7.9 ± 0.5</td>
</tr>
</tbody>
</table>

Table 6 – Comparison between the incidence angle modifiers obtained by the steady-state and quasi-dynamic test methods

<table>
<thead>
<tr>
<th>Collector</th>
<th>Método</th>
<th>IAM (50°) Longitudinal</th>
<th>IAM (50°) Transversal</th>
<th>IAM (20°) Transversal</th>
<th>IAM (40°) Transversal</th>
<th>IAM (60°) Transversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC 1</td>
<td>Steady-state</td>
<td>0.91 ± 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.89 ± 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FPC 2</td>
<td>Steady-state</td>
<td>0.85 ± 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>0.85 ± 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ETC DF</td>
<td>Steady-state</td>
<td>-</td>
<td>0.88 ± 0.01</td>
<td>1.02 ± 0.01</td>
<td>1.02 ± 0.01</td>
<td>1.10 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>-</td>
<td>0.90 ± N.A.</td>
<td>1.02 ± 0.01</td>
<td>1.03 ± 0.01</td>
<td>1.12 ± 0.01</td>
</tr>
<tr>
<td>ETC HP</td>
<td>Steady-state</td>
<td>-</td>
<td>N.A. ± N.A.</td>
<td>1.07 ± 0.01</td>
<td>1.33 ± 0.01</td>
<td>1.45 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>-</td>
<td>0.92 ± N.A.</td>
<td>1.06 ± 0.01</td>
<td>1.30 ± 0.01</td>
<td>1.47 ± 0.03</td>
</tr>
<tr>
<td>CPC</td>
<td>Steady-state</td>
<td>-</td>
<td>0.89 ± 0.01</td>
<td>0.95 ± 0.01</td>
<td>0.93 ± 0.01</td>
<td>0.60 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>-</td>
<td>0.78 ± N.A.</td>
<td>0.97 ± 0.01</td>
<td>0.94 ± 0.01</td>
<td>0.70 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Quasi-dynamic</td>
<td>-</td>
<td>0.87 ± N.A.</td>
<td>0.96 ± 0.01</td>
<td>0.91 ± 0.01</td>
<td>0.64 ± 0.01</td>
</tr>
</tbody>
</table>

In cases, the parameter \( c_{\text{opt}} \), which expresses the increase in thermal losses to the environment with air speed, had significance for the FPC and for the CPC collector but it didn't in the case of ETCs. This is an expected result precisely because the role of the vacuum is to create a barrier to energy transport by convection that in practical terms avoids the heating of the cover, as in FPCs or CPCs, lowering the exchanges with the environment. All the tests were conducted with artificial wind generators imposing a minimum flow at the collectors' surface for the sake of repeatability between tests. Air speed changes due to the natural wind speed may not be sufficient to consider the modeling of the behavior of the collector with it (relevant for tests of uncovered collectors). In conclusion, this parameter should not be regarded as a modeling parameter for collector but as a correction to the experimental conditions.

The IAM for direct radiation that was obtained was as expected for the different collector types. In FPCs it was adjusted to the equation (5) and the values
obtained for \( b_0 \) were in line with what is usual. For the ETCs it was considered a biaxial separation of the IAM and the values achieved in both directions were also in line with what is usual. For the CPC collector the value of \( b_0 \) was clearly wrong and it was correlated with the parameter \( c_2 \). According to the regression, the parameter \( c_2 \) was much more significant than the remaining losses. This has to do with the fact that the values measured by pyrometer in the day in which the slope of the collector was greater are higher than in the other days. This observation shows the danger that comes from the first approach to parameter identification to be executed with the complete model. Contrary to the EN 12975-2 standard instructions, this case had to be recalculated, excluding the parameter \( c_2 \) from the model despite its statistical significance. Some issues related to the determination of the IAM are detailed in section (5.4).

The IAM for diffuse radiation was significant in all cases, which proves the importance of the decomposition of the global incident radiation on the direct and diffuse components. The values obtained were the expected ones, less than a unity for the FPCs and CPC and more than one for the ETCs.

Regarding the parameters \( c_1 \) and \( c_2 \) the only detail worth highlighting is the case of the ETC HP collector, for which \( c_2 \) had a lower value than its standard uncertainty. The EN 12975 standard requires the value of \( c_2 \) to be presented (even if it is negative), contrary to what is stated for steady-state test. In a revision of the standard this should be corrected and the rule adopted for the steady-state test should be applied to the quasi-dynamic test.

5.2. Comparison between methods

The comparison of power curves, obtained from the parameters of the steady-state test and the values calculated based on the quasi-dynamic test, validates the quasi-dynamic model and demonstrates its adequate implementation. The curve of the quasi-dynamic model is located, in most cases, in the range defined by the curve of the steady-state model more or less one standard deviation. The differences observed are within the values indicated in the literature (Fischer et al. 2004; Rojas et al. 2008; Fischer & Müller-Steinhagen 2009) and are in the order of those obtained when performing independent tests to the same collector.

Another characteristic referenced in the literature (Perers 1997) is the correlation between the losses parameters, i.e., between the coefficient of losses and the temperature of this coefficient on the temperature. The clearest cases in which there is a "compensation" are the FPC 1 with quasi-dynamic test parameters of 3.9 and 0.015 and steady-state parameters of 4.6 and 0.008 and the ETC HP collector with 2.8 and 0.003 to 1.8 and 0.015 for the \( a_1 \) and \( a_2 \) coefficients respectively. In the ETC HP collector, the power curve from the steady-state test is more "parabolic" than usual for a vacuum tube collector, which can be explained by the fact that the maximum test temperature is not very high (in this case \( t_{\text{min}}=70 \, ^\circ\text{C} \)), thereby preventing a good definition of the curve for higher temperatures. The fitting of the power curve of the steady-state model is a function of reduced temperature \( T^{*}(t_{\text{min}}-t_{\text{max}})/G \) obtained with a radiation of about 1000 W/m², while the quasi-dynamic test admits much lower radiation that would be equivalent to much higher reduced temperatures.

Even if one cannot draw definitive conclusions with only a few collectors tested, it was observed that when the thermal capacities are low (as is the case for FPC 1, FPC 2 and CPC, with values of 9.6, 7.8 and 8.7), the quasi-dynamic test overestimates the value of the thermal capacity with relation to the steady-state test (for which 8.3, 6.6 and 7.5 values were obtained, respectively). When the thermal capacities are high, as for vacuum tube collectors, particularly those with heat pipes, the trend is exactly the opposite. The ETC DF collector showed a thermal capacity of 30.6 in the quasi-dynamic test and 37.6 in the steady-state test. The calculated thermal capacities for the ETC HP collector were 65.2 and 101.2, respectively.

The results for IAM are in agreement between the two methods, with the exception of the first processing of data for the CPC collector, for the reasons mentioned earlier. In Table 5 and Table 6 the expected corrections to results are shown, with major impact in the parameter \( b_0 \) longitudinal and consequently the longitudinal IAM (50 °C).

5.3. Thermal capacity

The great simplicity of the quasi-dynamic model results from its ability to model a collector subjected to changing conditions while it is not, in fact, a dynamic model. Within the time interval where the average values of the recorded quantities are calculated it is assumed that the power supplied by the collector is independent of what happened before that interval. Some collectors have high or very high thermal capacities, such as the vacuum tube collectors ETC DF (30.6 kJ/(m²K)) and ETC HP (65.2 kJ/(m²K)). In these cases, the time that the collector takes to react and adapt to a new radiation condition is very large and can exceed the period of the integration interval. Thus, the model cannot accurately represent the behavior of the collector.

The sensitivity of the model to variations in the mean temperature is also significantly increased due to the parameter \( -c_{\text{rad}}dT/dt \) and the modeled power oscillates around the experimental power.

Consider the following situation that commonly occurs: the inlet temperature is not exactly constant and in a given 5 min interval varies, let's say, by 0.2 °C. At a constant radiation condition, this variation is followed by the output and, therefore, the fluid mean temperature increases or decreases by about 0.2 °C.

Considering the thermal capacity of the ETC HP collector, the model will make a correction of 43 W that is not representative of any change to the operating conditions. This will result in the oscillating effect that can be observed in Fig. 3. The same calculation for the collector CPC 1, results in a correction of 6 W that has much less impact.

These two situations can be mitigated, but not eliminated, by using the maximum interval of integration allowed by the EN 12975-2 standard (10 min). For the ETC HP collector the experimental data were condensed in 10 min intervals and the new data were analyzed. The graph of experimental and modeled power is shown in Fig. 4.

This collector is outside the limits where the clause 6.3 the EN 12975 standard should be applied. Further work is needed to adapt the quasi-dynamic test methodology to these collectors.
5.4. Incidence Angle Modifier

The high thermal capacity of some collectors also influences the test for determining the IAM in the transversal direction. In the longitudinal direction, at any time of the year, the evolution of the angle of incidence over time takes place slowly. In the transversal direction it is often about 2.5° in 10 min. The large angles of incidence are determined at the beginning or end of the day, when solar radiation increases or decreases even if measured in the perpendicular plane. When a collector has a high thermal capacity, its state in a given period is not characterized only by radiation in that period, as mentioned above. In the setting of large incidence angles and varying radiation, the impact of high thermal capacity in the determination of the IAM is such that the IAM value is undervalued in the early morning and overvalued in the late afternoon. This effect is common to the quasi-dynamic and steady-state tests, as shown for the ETC HP collector in Fig. 5. The ETC DF collector showed the same effect.

Symmetry in relation to the longitudinal plane was considered for the IAM and the final values represent an average of data from the morning and afternoon, both in the case of the steady-state and the quasi-dynamic tests. Thus, a fundamental rule in the tests of this type of collectors is to acquire experimental data roughly symmetrical to the solar noon to prevent biased results.

In Fig. 6 the curve corresponding to the equation 1/cos(θ) is also presented. This curve is interesting when evaluating vacuum tube collectors without reflector, as these are cylindrical tubes (with cylindrical absorbers) and for much of the day show the same intersection area to the solar radiation. The equation 1/cos(θ) only resets the radiation incident on the plane of the collector to the value it has on the plane perpendicular to the direction Earth-Sun (Tang et al. 2009). This approach, purely geometric, would avoid tests with angles of 20 and 40°, when performing the steady-state test method for this type of collectors.

The chart values were obtained using the experimental data and the calculated parameters and inverting the model equation for the IAM of direct radiation. The values of IAM obtained by the regression for the different angle intervals are also presented. The values for the steady-state test are obtained by inversion of the equation (16).

Fig. 6 – IAM for the direct radiation over the transversal direction for the CPC collector

Fig. 6 show the agreement between the IAM values obtained by the two methods and has the interesting characteristics that the test has been conducted very close to the equinox, which allowed the characterization of the entire range of the curve. The collector is a CPC with a concentration ratio of 1,12x, an acceptance angle of 56.4° before truncation and 76° after truncation.
These angles are plotted as lines in Fig. 6 and agree with the experimental data.

6. Conclusions

The advantage of the quasi-dynamic test over the steady-state test in terms of the number of days available for testing throughout the year was investigated on the basis of meteorological data collected at the LES. These data series exist, with almost no flaws, since 2007 to the present time. It was concluded that it will be possible to test approximately twice the number of collectors annually, with special relevance during the autumn and winter months, when the number of collectors that can be tested nearly triples. For a testing laboratory in which the test circuits are limited in number, this is an important aspect, both in terms of total annual capacity and in the distribution of work over the year.

The experimental implementation of the quasi-dynamic test method was performed carefully following the guidelines and test requirements of the EN 12975-2:2006 standard. For data acquisition, a software program was developed. After the necessary tools had been developed an intensive experimental work was then carried out that consisted in testing five collectors according to the two test methods over 43 valid days. Different types of collectors were deliberately chosen, two flat plate collectors, an evacuated tubular collector with direct circulation and a back reflector, an evacuated tubular collector with heat pipes and a CPC collector, so that collector-specific questions could be investigated, both experimentally and during analysis and data processing.

The experimental data have been thoroughly analyzed and the model's characteristic parameters were identified by Multiple Linear Regression. Good fits were obtained for all collectors with a maximum residue of 34 W/m² for the ETC HP collector but less than 15 W/m² for the others. The methodology for handling experimental uncertainties was investigated.

The recommendations by the EN 12975 standard to be used for the comparison of quasi-dynamic and steady-state methods impose a condition of 15 °C for the angle of incidence and 3 m/s of air speed. These conditions don't match the conditions of the steady-state tests and were corrected. Therefore, an angle of 0 ° and a mean value for the air speed during the steady-state data collection were used instead. The parameters obtained for the comparison between the results of the two test methods have revealed a good agreement. The power curves of the collectors were drawn and the curve of the quasi-dynamic test is, in most cases, within the range defined by the steady-state curve more or less one standard deviation. Throughout the analysis of the results of this work, some problems were identified for which suggestions were given to improve the text of the standard, the test methodology and the data analysis. The main issues identified relate to: a) the statistical significance associated with a parameter in the MLR is not always meaningful and the technician needs to understand whether there is a strong correlation between experimental parameters, in which case the parameter should be abandoned and the regression redone; b) when the parameter associated with the dependence of thermal losses on temperature ct has no significance, it should be rejected as it is done in the steady-state test with the parameter α2. c) there should be a limit to the effective collector heat capacity, because when its time constant is too high, the modeling of the parameter c2 in the quasi-dynamic model fails, even when the upper limit of the integration (10 min) is used; d) for the collectors with high thermal capacity, the IAM test is required to be performed by acquiring experimental points that are symmetrical with regard to solar noon.

The IAM test to the CPC collector held near the equinox enabled a complete characterization of the curve which was compared, in terms of the cutting angles obtained based on the theoretical design of the cavity, having been obtained consistent results.

7. References


