COMPARISON OF THERMAL EFFICIENCY CURVES OF SOLAR COLLECTORS TESTED IN OUTDOOR CONDITIONS

Alberto García de Jalón, Fabienne Sallaberry, Xabier Olano, Enric Mateu, Roberto Astiz, María Ezcurra and Lourdes Ramírez

Solar Thermal Energy Department, National Renewable Energy Centre (CENER), Sarriguren (Navarra), Spain

1. Abstract

The Solar Thermal Testing Laboratory (LEST) of CENER has been performing durability and efficiency tests on solar collectors since 2004 according to the European Standard EN 12975-2. This standard describes different testing methods to determine the thermal efficiency curve of solar collectors. The LEST is an, by the Spanish Accreditation Entity (ENAC), accredited laboratory for performing thermal efficiency curves in steady and quasi-dynamic states according to parts 6.1 and 6.3 of the standard EN 12975-2, respectively. In this paper, we focus our work on tests carried out in outdoor conditions under both methodologies. We will analyze the differences of thermal efficiency curves for two different kinds of solar collectors.

In 2010, the LEST conducted different thermal efficiency tests on one flat plate collector and also on an evacuated tube collector. Both solar collector technologies were tested under quasi-dynamic and steady state conditions according to EN 12975-2 requirements. We will analyze the differences obtained by testing the same collector with both methodologies. Another important objective of this paper has been to know the influence of selecting different data sets in order to characterize the optical and thermal properties of two solar collectors tested under quasi-dynamic conditions.

The aim of this paper is to confirm that the present outdoor efficiency test methodologies proposed by the EN 12975 are fully compatible with flat-plate and evacuated tube collectors.

2. Introduction

The performance model equation for a solar thermal collector is defined in part 6.1 in steady-state conditions and in part 6.3 in quasi-dynamic state conditions of EN 12975-2 standard. The efficiency curve test of a solar collector consists basically of circulating a heat transfer fluid through the absorber at different inlet temperatures, under the same radiation and flow rates. The mean physical measured and registered data are: solar radiation (global G and diffuse G_d), ambient temperature t_a, inlet temperature t_{in} , outlet temperature t_e, mass flow rate $\dot{m}$ and wind speed over the collector plane. For quasi-dynamic tests, the relative thermal radiation E_L is also recorded. Each testing period is called a "data point", and we need to vary the inlet temperature in order to draw an efficiency curve for a reduced temperature X = $(t_m-t_a)/G$ from 0 to at least 0,06 K m^2/W.

3. Description of testing methods

3.1. Description of the model under quasi-dynamic conditions

The efficiency model under quasi-dynamic conditions is:

$$\eta = F'(\tau\alpha)_{en} K_{\theta_b}(\theta)\frac{G_b}{G} + F'(\tau\alpha)_{en} K_{\theta_d}\frac{G_d}{G} - c_1\frac{(t_m - t_a)}{G} - c_2\frac{(t_m - t_a)^2}{G} - c_3 u\frac{(t_m - t_a)}{G} - c_4\frac{(E_L - \sigma T_a^4)}{G} - c_5\frac{dT_m/dt}{G} - c_6 u \quad \text{(eq. 1)}$$

This model, according to part 6.3 of the standard, takes into consideration the dependency of the unglazed collector on the wind speed, and on the relative radiation. Parameters c_3 and c_6 are equivalent to parameters b_2 and b_u in part 6.2 of the Standard for unglazed collectors. As CENER mainly tests glazed collectors at wind speeds between 2 and 4 m/s using artificial wind generator, this dependency is negligible. So, in the case of glazed collectors, the coefficient of the dependence on wind speed and the relative solar thermal radiation can be neglected. Then, the equation model may be reduced to:

$$\eta = F'(\tau\alpha)_{en} K_{\theta_b}(\theta)\frac{G_b}{G} + F'(\tau\alpha)_{en} K_{\theta_d}\frac{G_d}{G} - c_1\frac{(t_m - t_a)}{G} - c_2\frac{(t_m - t_a)^2}{G} - c_5\frac{dT_m/dt}{G} \quad \text{(eq. 2)}$$

For the outdoor quasi-dynamic method, every mean interval (5-10 minutes) is a data point, and over 300 data points with variability in all ambient conditions (inlet temperature, wind speed, diffuse radiation) are necessary.

Fig. 1: Outdoor quasi-dynamic testing bench

To compare the test results obtained in quasi-dynamic state regarding the results of the steady state test, the test results shall be presented in the form of a power curve as a function of the temperature difference between mean fluid and ambient temperature (t_m–t_a), using values G = 1000 W.m^{-2}, G_b = 850 W.m^{-2}, G_d= 150 W.m^{-2}, θ=15º, dT_m/dt = 0, u = 3 m/s and E_L-σT_a^4 = - 100 W.m^{-2}, in equation 3:

$$\eta = \eta_0 + a_1\frac{(t_m - t_a)}{G} + a_2\frac{(t_m - t_a)^2}{G} \quad \text{(eq. 3)}$$

where,

$$\eta_0 = \mathrm{F'}(\tau\alpha)_{\mathrm{en}} K_{\theta_b}(\theta)\cdot\frac{G_b}{G} + \mathrm{F'}(\tau\alpha)_{\mathrm{en}} K_{\theta_d}\cdot\frac{G_d}{G} - c_5\cdot\frac{dT_m/dt}{G} = \frac{\mathrm{F'}(\tau\alpha)_{\mathrm{en}}}{G}\left(K_{\theta b}(\theta)G_b + K_{\theta_d}G_d\right)$$

$$a_1 = -c_1$$

$$a_2 = -c_2$$

3.2. Description of the outdoor model under steady-state conditions

For the outdoor steady-state method, 4 data points per inlet temperature for a total of 16 points are necessary. The thermal performance curve is calculated using the matrix method multiple linear regression model equation (4):

$$\eta = \frac{\dot{Q}}{A_a \cdot G} = \frac{\dot{m} c_f (t_e - t_{in})}{A_a \cdot G} = F'(\tau\alpha)_{en} \frac{G_b}{G} + a_1 \cdot \frac{(t_m - t_a)}{G} + a_2 \cdot \frac{(t_m - t_a)^2}{G} \quad \text{(eq. 4)}$$

A collector is considered to operate in steady-state conditions over a given measurement period if none of the experimental parameters deviate from their mean values over the measurement period by more than the limits given in table 1:

Tab. 1: Permitted deviation of measured parameters during a measurement period

Parameter	Permitted deviation from the mean value
Test solar irradiance (Global)	$\pm$ 50 W.m^{-2}
Surrounding air temperature (indoor)	$\pm$ 1 K
Surrounding air temperature (outdoor)	$\pm$ 1,5 K
Fluid mass flow rate	$\pm$ 1 %
Fluid temperature at the collector inlet	$\pm$ 0,1 K

To establish that a steady state exists, average values of each parameter taken over successive periods of 30 seconds shall be compared with the mean value over the measurement period.

Fig. 2: Outdoor steady state test bench with solar tracker

3.3. Collector samples

The tests have been performed on two typical low temperature solar collectors. Tests were performed on a flat plate collector and evacuated tube collector. We describe the technical characteristics of each collector:

Tab. 2: Technical characteristics of tested collectors

Type	Flat plate with cover	Asymmetric direct vacuum tubes collector with reflector
Aperture Area	2,25 m^2	2,01 m^2
Absorber	Grid of 9 x 2 tubes welded to a copper plate with Black Chrome selective treatment	Double concentric glass tube with selective treatment and copper foil in contact with pipes flow

Fig. 3: Solar collectors tested

4. Measurement results

Each test sample was subjected to a thermal performance test according to quasi-dynamic and steady state methods. A comparison of the results obtained for each collector was evaluated regarding the two different testing methods.

4.1 Flat Plate Collector:

Steady-State method

The thermal performance test was performed according to part 6.1 of the standard EN 12975-2 under steady outdoor conditions between 15/07/2010 to 20/07/2010. The results of the coefficients that characterize the efficiency curve are:

Tab. 3: Efficiency curve values, steady-outdoor conditions

η_0 [-]	$u(\eta_0)$ [-]	a_1 [(m^2K)/W]	$u(a_1)$ [(m^2K)/W]	a_2 [(m^2K^2)/W]	$u(a_2)$ [(m^2K^2)/W]
0,726	± 0,004	4,05	± 0,26	0,015	± 0,004

Quasi-dynamic method

The thermal performance test was performed according to part 6.3 of the standard EN 12975-2 under quasi-dynamic conditions between 21/06/2010 to 05/07/2010. In this period of time, different inlet temperatures have been tested to have enough days for three different treatments that meet the requirements of the standard.

Tab. 4: Different quasi-dynamic combinations groups

Date	Group 0	Group 1	Group 2
21/06/2010	X	X	
22/06/2010	X	X	
23/06/2010	X	X	
24/06/2010	X	X	
25/06/2010	X		X
28/06/2010	X		X
29/06/2010	X		X
30/06/2010	X		X
01/07/2010	X	X	
02/07/2010	X	X	X
05/07/2010	X		

The results of these three possible combinations are:

Tab. 5: Efficiency curve values for different quasi-dynamic combinations groups

Parameters	Group 0	Group 1	Group 2
η_0 [-]	0,715	0,715	0,715
a_1 [(m²K)/W]	3,911	4,118	3,721
a_2 [(m²K²)/W]	0,013	0,009	0,017

Comparison method:

To compare the results obtained in both test methods we have calculated the thermal performance of the collector according to equation (4) from a temperature difference $(t_m-t_a)/G$ from 0 to 0,06 Km^2/W. The efficiency curve representation is normalized for G = 1000 W/m^2, the final results are indicated in table 6.

We believe that this method of comparison is more coherent and realistic than comparing the representative coefficients of the efficiency curve obtained in each test method, independently. In some cases efficiency curves coefficients that apparently may seem different, represent thermal performance curves which are similar because their regression coefficients are compensated.

Tab. 6: Thermal Efficiency comparison for quasi-dynamic and steady-state test methods

$(t_m-t_a)/G$ [Km^2/W]	Efficiency η [-]		Absolute difference in percentage points $\lvert \eta_{max} - \eta_{min} \rvert$*100
	Outdoor Steady-state	Quasi-dynamic	
0	0,725	0,715	1,0
0,01	0,682	0,674	0,8
0,02	0,636	0,631	0,5
0,03	0,588	0,585	0,3
0,04	0,536	0,537	0,1
0,05	0,482	0,486	0,4
0,06	0,425	0,432	0,7

Table 6 shows that the maximum difference is 1,0 percentage points from (tm-ta)/G = 0 to 0,06 Km^2/W. These differences are considered acceptable as the estimation of the performance uncertainties in both curves are similar to the differences observed between both methods. The efficiency curve selected for the quasi-dynamic method has been the group 0 which represents all the tested days.

Fig. 5 shows also similar representation of efficiency curves and a very high compatibility index between the two test methods.

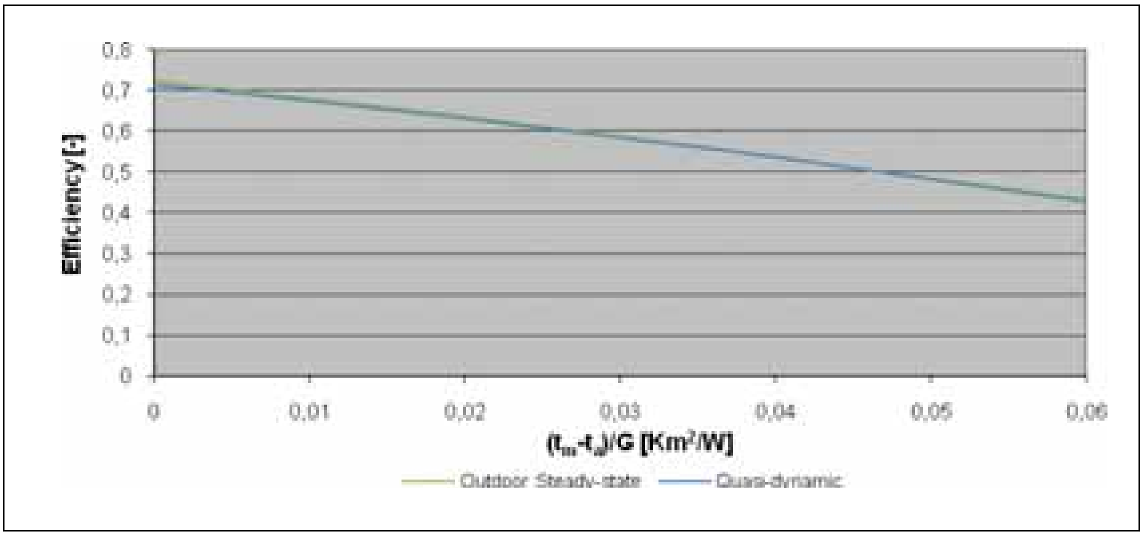

Fig. 5: Comparison graph of a thermal performance for flat plate collector tested according to the outdoor steady-state and quasi-dynamic methods.

As we indicated in Table 5, the collector has been characterized under quasi-dynamic conditions in three different day groups. Table 7 shows a comparison of the observed differences.

Tab. 7: Efficiency curve value comparison for different quasi-dynamic combination groups

$(t_m-t_a)/G$ [Km^2/W]	Efficiency η [-]			Absolute difference in percentage points $\lvert\eta_{max} - \eta_{min}\rvert*100$
	Group 0	Group 1	Group 2	
0	0,715	0,715	0,715	0,0
0,01	0,674	0,673	0,676	0,3
0,02	0,631	0,63	0,634	0,4
0,03	0,585	0,584	0,588	0,4
0,04	0,537	0,537	0,539	0,2
0,05	0,486	0,488	0,486	0,2
0,06	0,432	0,437	0,43	0,7

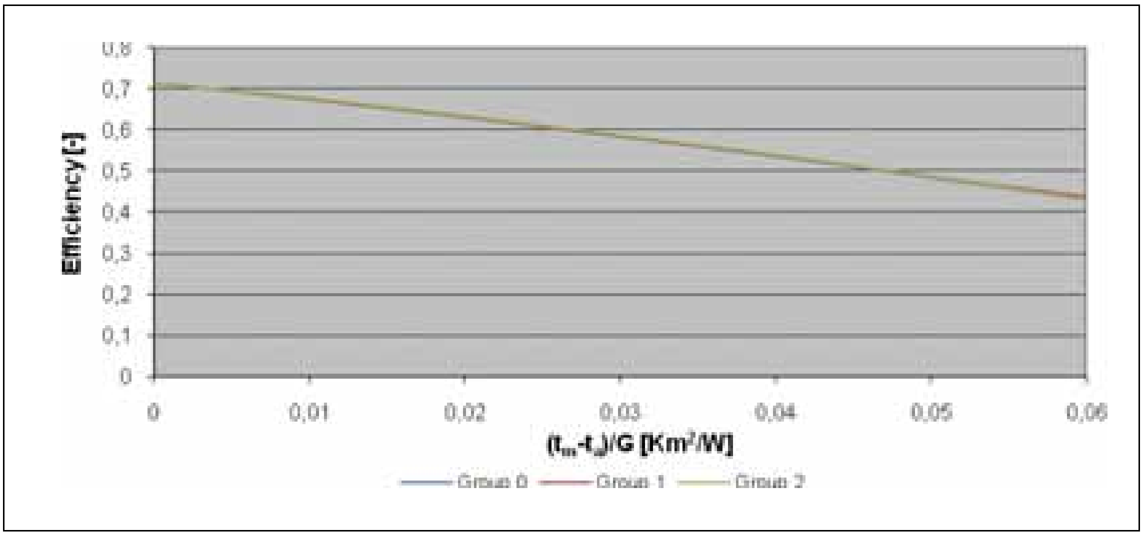

Fig. 6: Comparison graph of three different characterizations of the thermal performance flat plate collector tested according to quasi-dynamic method.

Table 7 and Fig.6 show that the maximum difference is 0,7 percentage points from $(t_m-t_a)/G$ = 0 to 0,06 Km^2/W. These differences are considered acceptable as the estimation of the performance uncertainties in all curves are similar to the differences observed among the three groups of data. In this comparison we can also see that although the coefficient characterization for groups 1 and 2 (table 5) apparently could differ when the thermal performance for the same group is represented, according the expression (4), the efficiency curves are really close because coefficients are compensated in the three cases.

4.2 Evacuated tube collector

Steady-State method:

The thermal performance test was performed according to part 6.1 of the standard EN 12975-2 under steady-outdoor conditions between 29/06/2010 to 01/07/2010. The results of the coefficients that characterize the efficiency curve are:

Tab. 8: Efficiency curve values, steady-outdoor conditions

η_0 [-]	$u(\eta_0)$ [-]	a_1 [(m²K)/W]	$u(a_1)$ [(m²K)/W]	a_2 [(m²K²)/W]	$u(a_2)$ [(m²K²)/W]
0,616	± 0,002	0,709	± 0,238	0,009	± 0,004

Quasi-dynamic method:

The thermal performance test was performed according to part 6.3 of the standard EN 12975-2 under quasi-dynamic conditions between 14/07/2010 to 09/08/2010. In this period of time, different inlet temperatures have been tested to have enough days to get three different treatments that meet the requirements of the standard.

Tab. 9: Different quasi-dynamic combination groups

Date	Group 0	Group 1	Group 2
14/07/2010	X	X	
15/06/2010	X	X	
16/06/2010	X	X	X
19/06/2010	X	X	
20/06/2010	X	X	
23/06/2010	X		X

26/06/2010	X		
27/06/2010	X	X	X
28/07/2010	X	X	X
10/07/2010	X		X
11/07/2010	X		
16/07/2010	X		
17/08/2010	X		
18/08/2010	X		
05/08/2010	X		X
06/08/2010	X		X
09/08/2010	X		X

The results of these three possible combinations are:

Tab. 10: Efficiency curve values for different quasi-dynamic combination groups

Parameters	Group 0	Group 1	Group 2
η_0 [-]	0,611	0,613	0,613
a_1 [(m²K)/W]	0,603	0,913	0,970
a_2 [(m²K²)/W]	0,007	0,000	0,000

Comparison method:

To compare the results obtained in both test methods we have calculated the thermal performance of the collector according to equation (4) from a temperature difference $(t_m-t_a)/G$ = 0 to 0,06 Km^2/W. The efficiency curve representation is normalized for G = 1000 W/m^2, the final results are indicated in table 11.

Tab. 11: Thermal Efficiency comparison for quasi-dynamic and steady-state test methods

$(t_m-t_a)/G$ [Km^2/W]	Efficiency η [-]		Absolute difference in percentage points $\lvert \eta_{max} - \eta_{min} \rvert$*100
	Outdoor Steady-state	**Quasi-dynamic**	
0	0,616	0,611	0,5
0,01	0,608	0,604	0,4
0,02	0,598	0,596	0,2
0,03	0,587	0,587	0,0
0,04	0,573	0,576	0,3
0,05	0,558	0,563	0,5
0,06	0,541	0,550	0,9

Table 11 shows that the maximum difference is 0,9 percentage points from $(t_m-t_a)/G$ = 0 to 0,06 Km^2/W. These differences are again considered acceptable as the estimation of the performance uncertainties in both curves are similar to the differences observed between both methods. The efficiency curve selected for the quasi-dynamic method has been the group 0 which represents all the tested days.

Fig. 7 shows also a similar representation of efficiency curves and a very high compatibility index between the two testing methods.

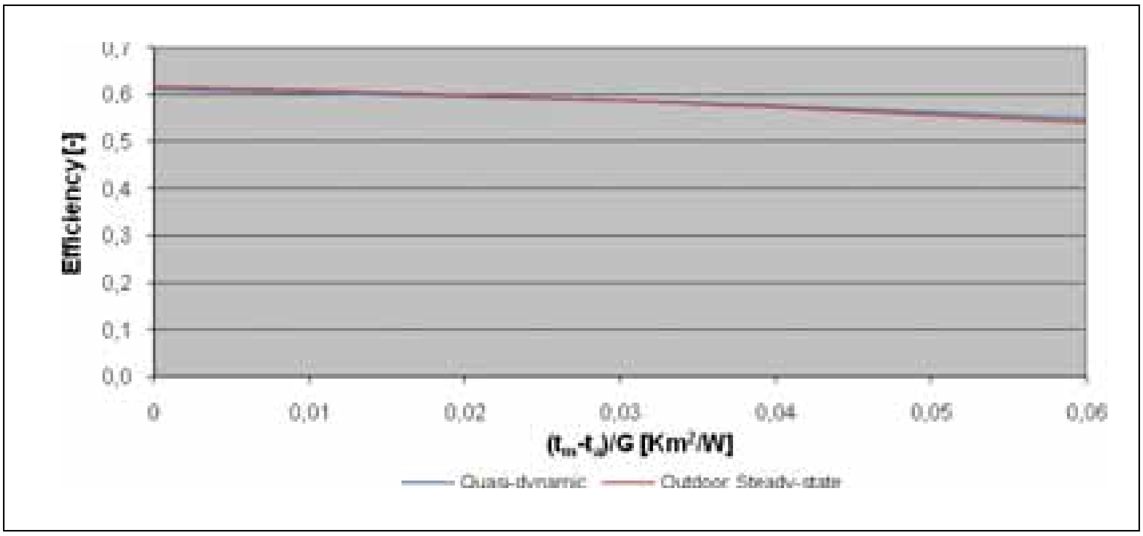

Fig. 7: Comparison graph of a thermal performance evacuated tube collector tested according to the outdoor steady-state and quasi-dynamic methods.

As we indicated in Table 9, the collector has been characterized under quasi-dynamic conditions in three different day groups. Table 12 shows a comparison of the observed differences.

Tab. 12: Efficiency curve value comparison for different quasi-dynamic combination groups

$(t_m-t_a)/G$ [Km^2/W]	Efficiency η [-]			Absolute difference in percentage points $\|\eta_{max} - \eta_{min}\|*100$
	Group 0	Group 1	Group 2	
0	0,611	0,613	0,613	0,2
0,01	0,604	0,604	0,603	0,1
0,02	0,596	0,595	0,594	0,2
0,03	0,587	0,586	0,584	0,3
0,04	0,576	0,577	0,574	0,3
0,05	0,563	0,568	0,565	0,5
0,06	0,550	0,558	0,555	0,8

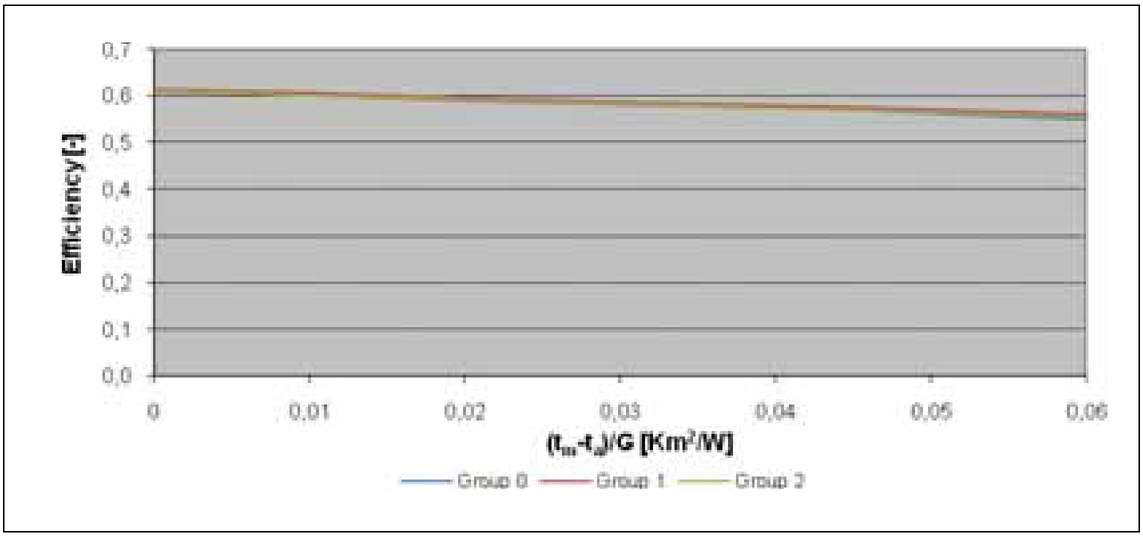

Fig. 8: Comparison graph of three different characterizations of the vacuum collector's thermal performance, tested according to quasi-dynamic method.

Table 12 and Fig.8 show that the maximum difference is 0,8 percentage points from $(t_m-t_a)/G = 0$ to 0,06 Km^2/W. These differences are considered acceptable as the estimation of the performance uncertainties in all curves are similar to the differences observed among the three groups of data. In this comparison we can see again that although the coefficient characterization of groups 0 and 2 (table 11) apparently differ when the thermal performance of the same group is represented, according to the expression (4), the efficiency curves are really close, due to compensated coefficients in the three cases.

5. Conclusions

After having tested both collectors under the two testing methodologies, and having analyzed the maximum differences regarding the thermal performance of the collectors, it can be concluded that:

- The test methodologies described in EN 12975-2:2006 regarding the determination of thermal performance in steady state or quasi-dynamic conditions are applicable and compatible with covered flat plate and evacuated tube collectors. In both cases, the maximum absolute difference has been of 1,0 percentage point for the range of temperature differences (tm-ta)/G = 0 to 0,06 Km2/W.
- The determination of the thermal performance, according to the expression 4 from the coefficients of thermal characterization for each collector, is confirmed as a comparative method which allows an accurate determination of the differences between the efficiency curves. In our case, we found data sets with apparently different loss coefficients that have very close efficiency curves, after calculating the thermal performance.
- A thermal performance test conducted according to standard EN 12975-2 can have different parameter identifications for the characterized collector coefficients depending on the selected data to determine its efficiency curve. However, the representation of the thermal performance curves or extracted power per collector unit reduces the differences observed when comparing the coefficients individually.

6. References

Standard ASHRAE 93:2010, Methods of testing to determine the thermal performance of solar collectors.

Standard EN 12975-1:2006, Thermal solar systems and components – Part 1: General requirements.

Standard EN 12975-2:2006, Thermal solar systems and components – Part 2: Test methods.