Comparison of solar collector thermal efficiency curves from different testing methods

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Abstract

The CENER Testing Laboratory has been performing durability and efficiency tests on solar collectors according to the European EN 12975-2 Standard since 2004. This Standard describes different thermal efficiency curve test methods. This laboratory is accredited for performing the thermal efficiency curve in indoor and outdoor test benches. In the paper, we analyze the difference of some efficiency curves found for some solar collectors using different efficiency tests according to both methodologies.

We show the results of the factor analysis for estimation of tested solar thermal optical efficiency according to the European Standard. Indoor tests with a solar simulator involve controlling of the spectrum of its lamps to ensure that the difference from the solar spectral distribution does not significantly change the optical efficiency of the solar collector. Solar collectors tests are done according to Parts 6.1 and 6.3 of the EN 12975-2 Standard, indoors with the continuous solar simulator or outdoors on a fixed or sun-tracking test bench. This study estimated the differences observed in the efficiency curves of some solar collectors, with different selective materials.

In this paper can be observed that the efficiency curves for the same collector have up to a 0,016 difference over the range tested (0 to 0,06 Km^2/W) for indoor conditions, and 0,010 for outdoor conditions.

Keywords: solar thermal collector, testing, certification, thermal efficiency curve.

1. Introduction

According to the Technical Building Code (CTE) and the Spanish Ministerial Order ITC/71/2007, for any solar collector on the Spanish market to be eligible for government subsidies must be homologated by Spanish Ministry of Industry, and to do so they must have passed all the tests in the European EN 12975-2 Standard for durability and efficiency tests. The CENER Solar Thermal Testing Laboratory in Pamplona has been accredited for performing the efficiency tests according to this European Standard since 2004. The general solar collector thermal performance model is well-defined in the Standard as thermal efficiency η dependence on the solar global irradiance G, the temperature difference between mean fluid collector temperature t_m and ambient air temperature t_a as follows:

$$\eta = \eta_0 - a_1 \cdot \frac{(t_m - t_a)}{G} - a_2 \cdot \frac{(t_m - t_a)^2}{G} \qquad (1)$$

With the mean temperature of the collector fluid is $t_m = (t_{in} + t_e)/2$

In order to ensure the quality of the results provided to its customers, the CENER Solar Thermal Testing Laboratory regularly makes internal comparisons of solar thermal collector thermal performance tests using both indoor and outdoor test benches according to the Part 6.1 of European Standard EN 12975-2. The purpose of this comparison is to analyze the physical causes of any difference in the efficiency curves found by each methodology and the respectively uncertainties. Analyzing all those results, we have observed, as discussed in the paper that there are different ways to compare efficiency curves, not only based on the characteristic parameters: optical efficiency η_0 and heat losses a_1 and a_2 but the interpretation of those differences taking into account the uncertainty of the sensors, the linear regression standard deviation and the difference in standard requirements.

2. Testing methods according to standard EN 12975-2

Estimation of the optical performance of a solar thermal collector is done by estimating the characteristic parameters of the theoretical performance model. The performance model equation for a solar thermal collector is defined in Part 6.1 of the Standard in steady-state conditions and in Part 6.3 in quasi-dynamic state conditions.

The efficiency test consists of measuring physical solar collector inlet and outlet during a testing period at least 4 times the time constant, or at least 15 minutes. The mean physical measured and registered data are the solar radiation G, the ambient temperature t_a, the inlet temperature t_{in} and outlet temperature t_e. For quasi-dynamic tests it is also recorded the relative thermal radiation E_L and the wind speed on the collector plane u. 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 Km^2/W.

2.1. Description of the model under quasi-dynamic conditions

The general efficiency model under steady-state conditions indoor and outdoor is for both the (2) expression. But, on the other hand, the efficiency model under quasi-dynamic conditions is:

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

This model according to Part 6.3 of the Standard takes into account the dependency of the unglazed collector on the wind speed and to 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 The CENER mainly tests glazed collectors at wind speed 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. The model may than be reduced to:

$$\eta = F'(\tau\alpha)_{en} K_{\theta_b}(\theta)\frac{G_b}{G} + F'(\tau\alpha)_{en} K_{\theta_d}\frac{G_d}{G} - c_1\frac{(t_m - t_a)}{G} - c_2\frac{(t_m - t_a)^2}{G} - c_5\frac{dT_m/dt}{G} \qquad (3)$$

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

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

For the outdoor stationary method 4 data points per inlet temperature for a total of 16 points, are necessary.

Fig. 1. Outdoor testing bench, Solar tracker

The efficiency model is similar to equation (1) but deleting the derivate of the mean temperature dT_m/dt as it is tested under steady-state conditions. We also observed that the optical efficiency η_0 enclose the diffuse radiation up to 30% as required in the European Standard:

$$\eta_0 = F'(\tau\alpha)_{en} K_{\theta_b}(\theta)\frac{G_b}{G} + F'(\tau\alpha)_{en} K_{\theta_d}\frac{G_d}{G} \qquad (4)$$

2.3. Description of the indoor model under steady-state conditions

For the indoor stationary method, 2 data points per inlet temperature, for a total of 8 points, are necessary.

For indoor tests, the CENER uses a 63 red simulator lamps that provide continuous radiation on the collector tested according to the requirements in Part 6.1.5.2 of the Standard with 15% spatial uniformity, with halide metal lamps having a spectral distribution similar to AM 1.5 sun spectrum, over 80 % of the radiation is collimated in a ±30º cone and a cold sky that reduces relative thermal radiation to less than 5% of the solar global radiation.

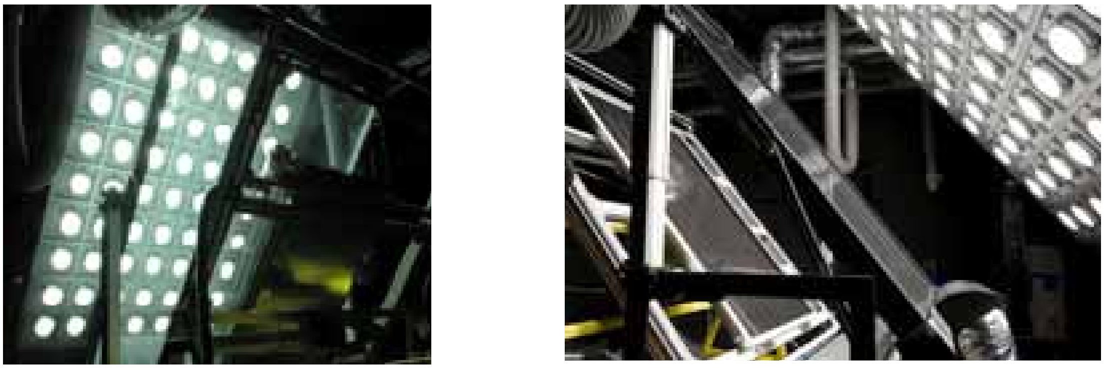

Fig. 2. Indoor testing bench, Continuous solar simulator.

For the indoor steady-state test, the efficiency expression can be simplified by the “optical efficiency” $\eta_0 = F'(\tau\alpha)_{en}$, as there is zero diffuse radiation in the simulator, the normal incidence angle and $dT_m/dt = 0$. Equation (3) is thus simplified to:

$$\eta = F'(\tau\alpha)_{en} - c_1 \frac{(t_m - t_a)}{G} - c_2 \frac{(t_m - t_a)^2}{G} \qquad (5)$$

However, the spectral distributions of the Sun and the solar simulator lamps are different. This difference may influence the measured $F'(\tau\alpha)_{en}$, since the product $(\tau\alpha)_{en}$ directly depends on the distribution of the radiation source. When a solar simulator is used and the collector has selective material for its cover and its absorber, a spectral correction must be applied to the optical efficiency parameter:

$$F'(\tau\alpha)_{en(SOL)} = F'(\tau\alpha)_{en(Sim)} \frac{(\tau\alpha)_{en(SUN)}}{(\tau\alpha)_{en(Sim)}} = F'(\tau\alpha)_{en(Sim)} C_{(\tau\alpha)} \qquad (6)$$

where $C_{(\tau\alpha)} = \dfrac{(\tau\alpha)_{en(SUN)}}{(\tau\alpha)_{en(Sim)}}$ is the correction applied to the indoor optical efficiency, $(\tau\alpha)_{en(SUN)}$ is the outdoor product of transmittance – absorptance and $(\tau\alpha)_{en(Sim)}$ is the same product indoors. $(\tau\alpha)_{en(SUN)}$ and $(\tau\alpha)_{en(Sim)}$ may be different in collectors with selective coatings, but according to EN 12975-2 it may not exceed 1%, and according to the ASHRAE 93-2001 Standard, it may not exceed 3%.

Moreover, this correction takes the dependency of outdoor diffuse radiation, which may be up to 30% in outdoor efficiency tests, into account.

In this paper we will define criteria to compare efficiency curves characterized by different testing method.

Based on this study, the CENER adapted his testing process to include the correction to the indoor optical efficiency, $\eta_{0(sim)}$, with the correction factor.

3. Results

3.1. Repeatability with the same testing method

In order to study its own testing process, the CENER includes recurrent checking for repeatability in its internal quality plan. The same glazed flat-plate collector, with selective coating and mineral wool insulation, was tested several times with the steady-state methodology according to Part 6.1 of the Standard for outdoor and indoor testing using a solar continuous simulator.

We repeated indoor and outdoor efficiency curves three times. In the following graphics show the efficiency curves using both the indoor and outdoor methodologies.

In this paper, we define a coefficient D in order to compare the maximum efficiency differences for $X=(t_m-t_a)/G$ between 0 and 0,06 Km^2/W every 0,01 Km^2/W. This distance is evaluated between every possible pairs of tested curves.

$$D = \max\left(\left|\eta_k(x) - \eta_j(x)\right|\right) \quad x(0{,}0.06) \quad x = \frac{(t_m - t_a)}{G} \qquad (7)$$

3.1.1. Indoor steady-state

Table 1. Repeated indoor efficiency coefficients for one collector.

Curves nº	**Indoor coefficients**		
	η_0	a_1	a_2
1	0,750	4,084	0,018
2	0,748	3,928	0,019
3	0,753	4,173	0,013
mean	0,750	4,062	0,017

Table 2. Indoor efficiency coefficients for one collector.

X = $(t_m-t_a)/G$ [Km^2/W]	**1**	**2**	**3**	**media**	**|1-2|**	**|2-3|**	**|1-3|**	**dif max**
0	0,750	0,748	0,753	0,750	0,002	0,005	0,003	0,005
0,01	0,707	0,707	0,710	0,708	0,001	0,003	0,003	0,003
0,02	0,661	0,662	0,664	0,662	0,001	0,003	0,003	0,003
0,03	0,611	0,613	0,616	0,613	0,002	0,003	0,005	0,005
0,04	0,558	0,560	0,565	0,561	0,003	0,005	0,007	0,007
0,05	0,501	0,504	0,512	0,506	0,003	0,008	0,011	0,011
0,06	0,440	0,444	0,456	0,447	0,004	0,012	0,016	0,016
max								**0,016**

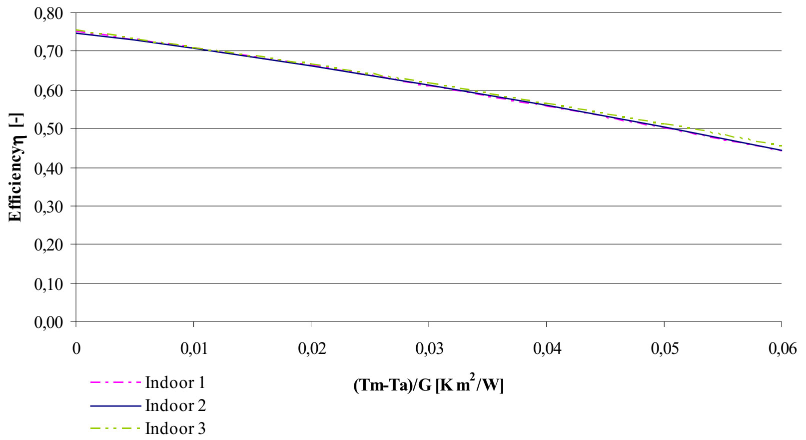

Fig. 3. Repeated indoor efficiency curves for 1one collector.

3.1.2. Outdoor steady-state

Table 3. Repeated outdoor efficiency coefficients for one collector.

Curves nº	**Outdoor coefficients**		
	η_0	a_1	a_2
1	0,735	4,549	0,01
2	0,733	4,716	0,004
3	0,739	5,193	0,0
mean	0,736	4,819	0,005

Table 4. Repeated outdoor efficiency coefficients for one collector.

X = $(t_m-t_a)/G$ [Km^2/W]	**1**	**2**	**3**	**media**	**|1-2|**	**|2-3|**	**|1-3|**	**dif max**
0	0,735	0,733	0,739	0,736	0,002	0,006	0,004	0,006
0,01	0,689	0,685	0,687	0,687	0,003	0,002	0,001	0,003
0,02	0,640	0,637	0,635	0,637	0,003	0,002	0,005	0,005
0,03	0,590	0,588	0,583	0,587	0,002	0,005	0,006	0,006
0,04	0,537	0,538	0,531	0,535	0,001	0,007	0,006	0,007
0,05	0,483	0,487	0,479	0,483	0,005	0,008	0,003	0,008
0,06	0,426	0,436	0,427	0,430	0,010	0,008	0,001	0,010
max								**0,010**

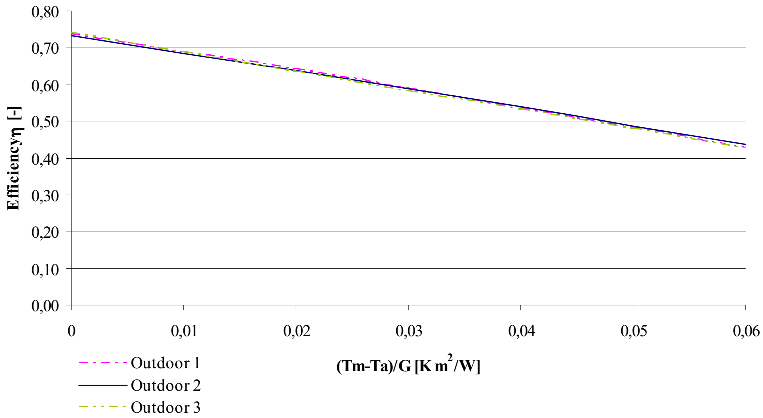

Fig. 4. Repeated outdoor efficiency curves for one collector.

We can observe that the curves are quite similar. The maximum efficiency difference outdoors is 0,010 and indoors 0,016 and in both cases the maximum reduced temperature is for X = 0,06 Km^2/W.

3.2. Indoor-outdoor efficiency curve comparison

We tested the efficiency curves of four different solar collectors indoors and outdoors. Collector n°1 is the same one used before for the repeatability test, and we chose two indoor and outdoor curves which were the closest to the mean parameters for this collector.

Table 5. Indoor and Outdoor efficiency coefficients for four collectors.

Collector n°	Absorber coating	Indoor			Outdoor			Maximum efficiency difference D (-)	Optical efficiency difference (-)
		η_0	a_1	a_2	η_0	a_1	a_2		
1	Selective	0,75	4,084	0,018	0,735	4,549	0,01	0,022	0,015
2		0,796	4,021	0,011	0,796	4,504	0,006	0,012	0
3	Black painting	0,749	6,642	0,016	0,713	6,428	0,028	0,066	0,036
4		0,741	6,351	0,019	0,714	7,122	0,004	0,037	0,027

Heat coefficients a_1 are observed to be quite similar, but the optical efficiencies and maximum difference in the curves are for Collectors 3 and 4.

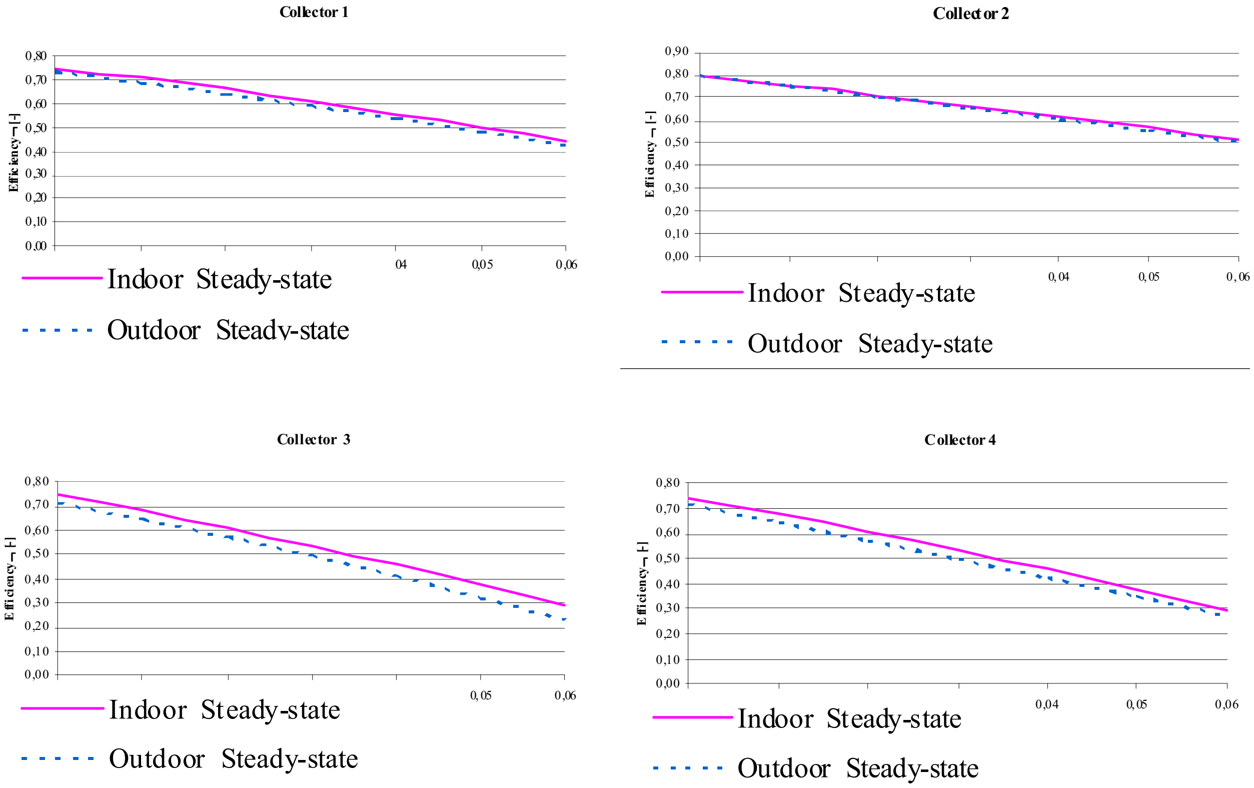

Fig. 5. Indoor and Outdoor efficiency curves for 4 collectors

5. Conclusion

The main conclusions are:

- The efficiency curves for the same collector can have up to a 0,016 difference over the range tested (0 to 0,06 Km^2/W) for indoor conditions, and 0,010 for outdoor conditions.
- The main differences between indoor and outdoor results seem to be related to black painting absorber coating.

References

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

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

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