COMPARISON TESTING OF A SOLAR SYSTEM WITH CSTG AND DST METHODOLOGIES

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1. Abstract

The Solar Thermal Testing Laboratory of CENER performs outdoor efficiency tests for factory-made solar systems according to international standard ISO 9459-2, using the CSTG method, as well as ISO standard 9459-5, using the DST method.

The first method (CSTG for "Collector and System Testing Group", also called Input-output method) consists of three different parts: one part for determining mixing in the storage tank during draw-off, another part for determining daily system performance, and the last part for the determination of storage tank heat losses.

The efficiency test in the DST method (also called Dynamic method) consists in different test sequences with different system behaviors: S-Sol for characterizing the collector array performance at high efficiencies, S-Store for characterizing store heat losses and collector array performance at low efficiencies and S-Aux for determining the heat losses and the volume fraction of the auxiliary heated portion of the store.

In both methods the result is a characterization of the solar system thermal behavior and then a long-term performance prediction. For the long term performance prediction, the thermal output energy of the solar system (Q) and solar fraction f_{sol} at on different reference locations and for different load volumes are calculated. In this study we tested two solar thermosyphon systems according to both methods.

The purpose of the paper is to show the results of the measuring output energy (Q_{med}) compared to the modelized output (Q_{mod}) and to analyze the system characterization obtained for each methodology. Then we will compare the long-term prediction results obtained for those two solar thermosyphon systems using both methods, as done in Carvalho et al. (2000) and Kaloudis (2010) et al.

We will analyze the causes of the maximum differences between both test methods for in the new results as well as in the context of the literature results. A new approach which includes the uncertainty derived of applying the literature conversion factors is proposed.

2. Introduction

According to the Spanish Technical Building Code (CTE) and Ministerial Order ITC/71/2007, all solar thermal systems on the Spanish market must be authorized by the Ministry of Industry to be eligible for government subsidies, and for this they have to pass all the UNE-EN 12976-2 European Standard tests. This Standard stipulates durability and efficiency tests, and user and installer documents to be checked.

The CENER Accredited Solar Thermal System Testing Laboratory in Seville has been performing all the tests for factory-made solar thermal systems according to the European Standard since 2008. And solar systems had been tested in this laboratory for 25 years before that.

The European Standard efficiency test refers to two ISO Standard, ISO 9459-2 (CSTG method) and ISO 9495-5 (DST method). The CSTG method, named for the group which originally developed it, "Complete System Testing Group", makes use of an input-output ratio, while the DST method, called the "Dynamic System Test", makes use of dynamic software for parameter identification.

The difference between both methods has been identified in the Standard EN 12976-2, based on the project EU-SMT "Bridging the Gap" presented in October 1999. This report presented some conversion factors for the long-term prediction results between both methods:

$$Q_{DST} = (a \pm \sigma_a) Q_{CSTG} \qquad \text{(eq. 1)}$$

For the thermosyphon systems these values are: $a = 1{,}056$ and $\sigma_a = 0{,}004$. In the paper, we will presented the test results on two thermosyphons according to both methods and check this conversion factor providing more experimental data.

3. Description of testing methods

3.1. Description of ISO 9459-2 test method

The first method (CSTG for "Collector and System Testing Group", also called Input-output method) is a "black box" procedure. It is applicable to solar-only and solar-preheat systems. It consists of three different parts: one part for determining daily system performance, another part for determining mixing in the storage tank during draw-off, and the last part for the determination of storage tank heat losses.

3.1.1. Determination of daily system performance

The daily system performance test consists in conditioning the system at least six hours before solar noon, circulating water in the tank until it is sufficiently uniform. Then, the solar system operates normally for 12 hours. Finally, six hours after solar noon, the tank water is drawn off until outlet and inlet temperatures are equalized, while the inlet water temperature is maintained constant.

The same test procedure is repeated until a set of one-day points is obtained with a sufficient range of daily solar radiation H and temperature difference $[t_{a(day)} - t_{main}]$. According to the Standard, the set should contain at least four different days with approximately the same values of $[t_{a(day)} - t_{main}]$ and daily solar irradiation values H evenly spread over the range between 8 MJ/m^2 to 25 MJ/m^2, and also contain at least two additional days with values of $[t_{a(day)} - t_{main}]$ at least 9 K above or below the values of $[t_{a(day)} - t_{main}]$ obtained for the first four days. The value of $[t_{a(day)} - t_{main}]$ shall be in the range - 5 K to + 20 K for each test day.

The mathematical model for the output energy production of the solar system Q dependst on daily solar irradiation H and the temperature difference between mean ambient temperature $t_{a(day)}$ and inlet water temperature t_{main} as following:

$$Q = a_1 H + a_2 \left(t_{\mathrm{a(day)}} - t_{main}\right) + a_3 \qquad \text{(eq. 2)}$$

The results consist of the coefficients a_1, a_2 and a_3 obtained by a multiple linear regression using the least-squares fitting method.

During each testing days, also the draw-off profiles are recorded and normalized for low and for high daily solar radiation days f(V).

3.1.2. Determination of the degree of mixing in the storage vessel during draw-off

The procedure aims to determinate the mixing draw-off profile g(V).

The test may be performed with the system mounted indoors or outdoors. If the test is performed outdoors, then the collector shall be shaded.

The test consists in conditioning the system, circulating water at a temperature above 60 ºC in the tank at a rate of at least five times the tank volume per hour until it is sufficiently uniform. The water in the store is assumed to be uniform when the outlet temperature and the inlet temperature vary by less than 1 K for a period of 15 min.

Afterwards, the storage tank is drawn off at a constant flow rate, while the inlet water introduced in the storage tank is maintained at a constant temperature of less than 30 ºC. The draw off volume should be at least three times the tank volume and until that the temperature difference between inlet and outlet water temperature is less than 1 K.

3.1.3. Determination of storage tank heat losses

The test consists in conditioning the system, by circulating water at a temperature above 60 ºC in the same way as the mixing draw-off test. Afterwards, the tank is left for cooling for a time period between 12 h and 24 h at night or without any incident solar radiation. During the cooling period, the air circulates freely over the collector's plane with a mean wind speed between 3 m/s and 5 m/s. After this cooling period, the water is again circulated in the same way in order to measure the drop of temperature suffered by the tank over the night.

The procedure aims to determinate the heat loss coefficient Us of the storage tank.

3.1.4. Prediction of long-term performance

With the total energy output characteristics of the system [a_1, a_2 and a_3], the normalized draw-off temperature profile [f(V)], the normalized mixing draw-off temperature profile [g(V)], the storage tank heat loss coefficient [Us], the daily meteorological data [daily solar irradiation H, daily mean ambient temperature $t_{a(day)}$, night mean temperature t_n] of the reference locations and the system characteristics [V_c], the performance of the system is calculated day-by-day for different reference locations and load demand.

3.2. Description of ISO 9459-5 test Method

The efficiency test in the DST method (also called dynamic method) consists in different test sequences with different system behaviors: S-Sol for characterizing the collector array performance at high efficiencies, S-Store for characterizing store heat losses and collector array performance at low efficiencies and S-Aux for determining the heat losses and the volume fraction of the auxiliary heated portion of the storage tank. Like in the CSTG method all the significant parameters (solar ration, inlet and outlet water temperature, ambient temperature, flow-rate) are recorded. The mathematical model of the system energy output is based on be described by a partial differential equation.

3.2.1. S-Sol Sequence

These sequence aims to characterize the collector array performance at high efficiencies. The test consists in conditioning the system and then letting the solar system operate normally for several days and finally doing the conditioning again to make uniform the tank temperature. Those sequence types are the called Test A and Test B. During those sequences a series of 5 or 7 draw-offs are executed with different durations according to the system characteristics and at different times of the day. The Test A is supposed to let the system work at high efficiencies with enough closed draw-offs to not let the collectors heat too much. The Test B is supposed to let the system work at low efficiency leaving the tank as warm as possible.

Within those sequences, there should be a minimum of valid days with enough daily solar radiation and outlet temperature higher then a minimum for Test B.

3.2.2. S-Store Sequence

This sequence aims to characterize the store heat losses parameter of the system. It consists of a Test B sequence for at least 2 days and a cooling period of for between 36 and 48 h.

3.2.3. S-Aux Sequence

This sequence aims to characterize the volume fraction of the auxiliary heated portion of the store. But it is not used in the tests of solar-only solar system as the thermosyphon.

3.2.4. Identification of system parameters and prediction of long-term performance

The identification of the characteristics parameters of the system is done using all the measured data recorded during the whole testing sequences. It is made by the validated commercial software InSitu (version 2.7) referred in the Standard ISO 9459-5.

The same software is used to calculate the yearly performance of the system for different reference locations and load demand using hourly meteorological data [H, t_a] of reference locations.

The results consist in the coefficients A_c* (effective collector area), u_c* (effective collector loss coefficient),

U_s (total store heat loss coefficient), C_s (total store heat capacity), D_L (mixing constant), Sc (store stratification). Each of those parameters is a coefficient of the terms in the physical model used for the thermosyphon.

3.3. Comparison

As the physical models of both methods are not the same, the parameters obtained can not be compared directly. The long-term prediction results gives both the demand load energy Q_d and the output energy Q_L from which we calculate the solar fraction $f_{sol} = Q_L / Q_d$. The comparison will be realized on the yearly output energy Q_L and a relation between the two methodologies results will be calculated.

$$\Delta Q_{\%} = \frac{\left(Q_{L(DST)} - Q_{L(CSTG)}\right)}{Q_{L(CSTG)}} * 100 \qquad \text{(eq. 3)}$$

For this comparison we use the load volumes referred in the Standard EN 12976-2 in the range between one half and one half higher than the storage tank volume. The reference locations are also referred in this Standard : Stockholm, Wuerzburg, Davos and Athens.

4. Experimental measurements

4.1. Experimental facilities and testing samples

The comparison of both methods was realized in CENER testing laboratory in Seville. The 4 testing benches are prepared to perform the system efficiency test according to both CSTG and DST methods.

For the comparison we use two only-solar systems. One is a thermosyphon with a storage tank of 300 l volume, and 2 flat-plate collectors with an aperture area of 3,81 m^2. The second is a thermosyphon too with a storage tank of 180 l volume, and 1 flat-plate collector with an aperture area of 1,95 m^2.

The first system was tested between 11/04/2011 and 01/05/2011 for CSTG and between 13/02/2011 and 10/04/2011 for DST. The second system was tested between 01/12/2010 and 19/12/2010 for CSTG and between 19/02/2011 and 24/03/2011 for DST.

For the long-term prediction we use load volumes from 170 l/day to 400 l/day for the first system and from 140 l/day to 300 l/day for the second system.

4.2. Results

We indicated in Tables 1 and 2 the systems parameters results.

Tab. 1: CSTG parameter identification

Parameter	System 1	System 2	Unit
a_1	1,89	0,98	m^2
a_2	0,57	0,37	$MJ.K^{-1}$
a_3	-2,11	-0,17	MJ

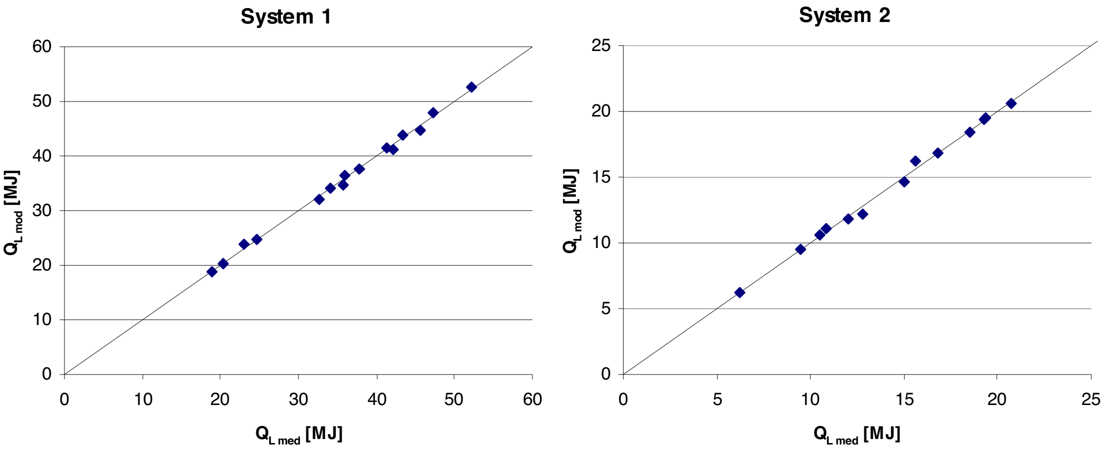

Fig. 1: Comparison graph of measured output energy $Q_{L\ med}$ vs modelized output energy $Q_{L\ mod}$ for the CSTG testing days

In both cases, the maximum difference between measured and modelized daily output energy for the testing days used in CSTG methods are less than 1 MJ/day.

Tab. 2: DST parameter identification

Parameter	System 1	System 2	Unit
A_c*	2,28	1,283	m^2
u_c*	5,986	10,83	$Wm^{-2}K^{-1}$
U_s	4,172	3,089	WK^{-1}
C_s	1,385	0,7885	$MJ.K^{-1}$
D_L	0,05055	0,01742	--
S_c	0,1131	0,2353	--

We indicated in Tables 3 and 4 the long-term prediction results.

Tab. 3: Long-term prediction for system 1

Location	Load volumes [l]	CSTG		DST		$\Delta Q_{L\%}$
		Q_d [MJ]	Q_L [MJ]	Q_d [MJ]	Q_L [MJ]	
Stockholm	170	9467	4199	9489	4903	17
Wuerzburg	170	9078	4617	9099	5247	14
Davos	170	10271	6782	10295	7714	14
Atenas	170	7055	5757	7071	6226	8
Stockholm	200	11138	4769	11163	5450	14
Wuerzburg	200	10680	5265	10705	5905	12
Davos	200	12084	7664	12112	8556	12
Atenas	200	8300	6608	8319	7084	7
Stockholm	250	13922	5580	13954	6198	11
Wuerzburg	250	13350	6202	13381	6817	10
Davos	250	15104	8889	15140	9666	9
Atenas	250	10375	7884	10398	8352	6
Stockholm	300	16706	6099	16745	6744	11
Wuerzburg	300	16020	6861	16058	7524	10

Davos	300	18125	9595	18168	10422	9
Atenas	300	12450	8888	12478	9407	6
Stockholm	400	22275	6487	22327	7227	11
Wuerzburg	400	21360	7391	21410	8224	11
Davos	400	24167	10063	24225	11055	10
Atenas	400	16600	10305	16637	10955	6

Tab. 4: Long-term prediction for system 2

Location	Load volumes [l]	CSTG		DST		$\Delta Q_{L\%}$
		Q_d [MJ]	Q_L [MJ]	Q_d [MJ]	Q_L [MJ]	
Stockholm	140	7796	3094	7814	3428	11
Wuerzburg	140	7476	3448	7494	3559	3
Davos	140	8458	4774	8479	4952	4
Atenas	140	5810	4387	5823	4477	2
Stockholm	170	9467	3405	9489	3829	12
Wuerzburg	170	9078	3848	9099	4019	4
Davos	170	10271	5214	10295	5478	5
Atenas	170	7055	5001	7071	5145	3
Stockholm	200	11138	3540	11163	4071	15
Wuerzburg	200	10680	4045	10705	4320	7
Davos	200	12084	5390	12112	5779	7
Atenas	200	8300	5456	8319	5669	4
Stockholm	250	13922	3627	13954	4173	15
Wuerzburg	250	13350	4147	13381	4460	8
Davos	250	15104	5512	15140	5886	7
Atenas	250	10375	5957	10398	6187	4
Stockholm	300	16706	3678	16745	4192	14
Wuerzburg	300	16020	4203	16058	4485	7
Davos	300	18125	5586	18168	5904	6
Atenas	300	12450	6170	12478	6383	3

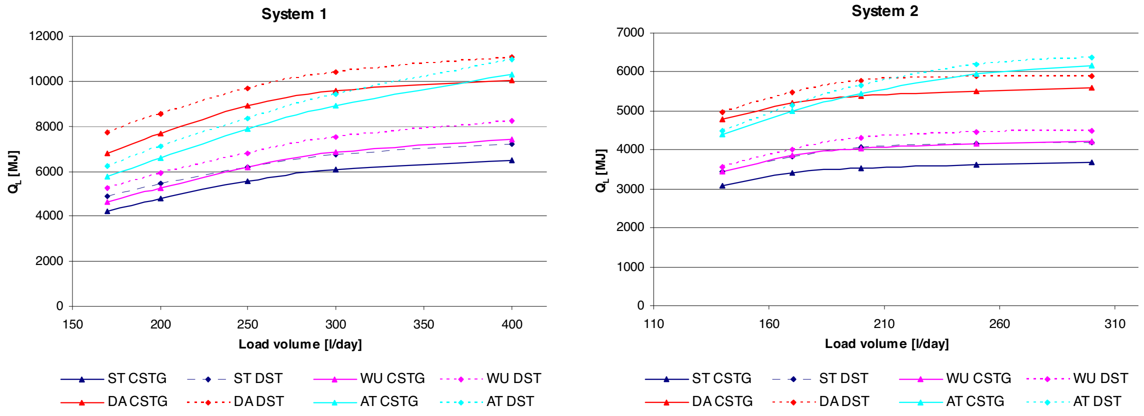

Fig. 1: Comparison graph of yearly output energy for the reference locations (ST: Stockholm, WU: Wuerzburg, DA: Davos and AT: Athens)

We observed differences up to 17% between both methods. According to Carvalho et al. (1999) the differences obtained had been up to 14% and according to Kaloudis et al. (2010) up to 21%. So we consider this difference as acceptable.

4.3. Conversion factor

We calculate the conversion factor as described in the equation 1 is: for system 1: a =1,094 and σ_a = 0,006; for system 2: a = 1,061 and σ_a = 0,008. The conversion factor obtained are higher than the one mention in the Standard EN 12976-2 (a = 1,056 and σ_a = 0,004). A combined conversion using both systems would be a = 1,084 and σ_a = 0,005.

Another way to compare the two methodologies would be using a constant difference as:

$$Q_{DST} = (b \pm \sigma_b) + Q_{CSTG} \quad \text{(eq. 4)}$$

We found for the two systems a main difference of b = 492 and σ_b = 244 MJ.

5. Conclusions

Two thermosyphon solar systems have been tested according to two different testing methodologies. The CSTG method according to international standard ISO 9459-2 is a Input-output method. The DST method according to international standard ISO standard 9459-5 is a dynamic method. In this study we have analyzed the maximum differences regarding the long-term prediction results and we concluded that:

- The differences observed between both test methodologies described in Standard ISO 9459-2 and Standard ISO 9459-5 are up to 17%.
- Those differences are considered acceptable as in the references all found similar differences are given.
- The conversion factor *a* found for the solar systems tested are higher than in Standard EN 12976-2.

The conversion factors could be added to the database of tests performed under both methods and thus contribute to re-calculate this factor in the Standard EN 12976 for future revisions of the Standard.

It is clear that the difference found shows that the DST methods gives better long-term prediction results than the CSTG method. For this reason it is important to apply the conversion factor when comparing a solar system tested with both methodologies

6. References

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