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Comparative analysis of domestic water heating thermosiphon systems tested according to the Standard ISO 9459-2

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Abstract

The Standard ISO 9459-2 is a standard for the characterization of thermal performance of domestic water heating systems without auxiliary heating. In this study, 18 domestic water heating thermosiphon systems have been tested according to this international standard. The objective of the paper is to carry out a comparative analysis of the results obtained in these systems as a function of their volume and type of heat exchanger (tubular and double jacket). A comparative analysis of systems performance will be carried out by calculating the performance without thermal loss (a_1/A) and solar fraction f_{SOL} in different reference locations for different volume/area ratios. Also, a comparative analysis of systems performance and solar fraction will be carried out at different locations between a tubular heat exchanger tank and a double jacket heat exchanger tank. The different values obtained will be compared for the storage tank's heat loss coefficient (U_s). It will determinate the useful energy (energy with temperature above 45ºC) for the degree of mixing in the storage tank during a draw-off test.

Keywords: solar system; testing; certification

1. 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 homologated by the Ministry of Industry to be eligible for government subsidies, and for this reason they have to pass all the tests from the European Standard EN 12976-2 European Standard tests. This Standard stipulates durability, safety and efficiency tests, user and installer documents checking.

The CENER (National Renewable Energy Centre) and GTER (Thermodynamic and Renewable Energies Group) Accredited Solar System Testing Laboratory in Seville have been performing all the tests for factory-made solar thermal systems according to the European Standard since 2008. The European Standard efficiency test refers to two ISO Standards, ISO 9459-2 (CSTG method) and ISO 9495-5 (DST method). The CSTG method, named after the group which originally developed it, "Complete System Testing Group", makes use of an input-output method, while the DST method, called the "Dynamic System Test", makes use of dynamic software for parameter identification of the system characterization.

The objective of this paper is to carry out a comparative analysis of the parameters and performance (η) of different domestic water heating systems (commercial systems) tested according to Standard ISO 9459-2. The systems have been classified according to their storage tank and type of heat exchanger (tubular and double jacket). A comparative analysis of systems performance by calculating the performance without

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thermal loss (a_1/A) and solar fraction f_{SOL} has been carried out at different reference locations for different volume/area ratios. Also, a comparative analysis of systems performance and solar fraction has been carried out at different locations between tubular heat exchanger tanks and double jacket heat exchanger tanks. It will compare the different values obtained for the storage tank's heat loss coefficient (U_s). It will determinate the useful energy (energy with temperature above 45ºC) for the degree of mixing in the storage tank during a draw-off test.

Manufacturers could make use of the results in order to study the potential improvements of their systems

2. Description of testing method (ISO 9459-2)

This 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 (part 2.1), another part for determining mixing in the storage tank during draw-off (part 2.2), and the last part for the determination of storage tank heat losses (part 2.3).

2.1. 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 depends on daily solar irradiation H and the temperature difference between mean ambient temperature $t_{a(day)}$ and inlet water temperature t_{main} as following:

$$Q = a_1 H + a_2 \left(t_{\mathrm{a(day)}} - t_{main}\right) + a_3 \quad \text{(eq. 1)}$$

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)*.

System performance (η) is defined as output energy production of the solar system (Q) divided by daily solar irradiation (H) and aperture area (A).

$$\eta = \frac{Q}{H \cdot A} \quad \text{(eq. 2)}$$

Performance without thermal loss is defined as (a_1/A), as $t_{a(day)}$ and t_{main} is equal and the value of a_3 is close to zero.

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

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, while the collector is shaded from the sun The water in the store is assumed to be uniform as 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 of 600 l/h, 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.

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

This test can provide information about the useful energy (Q_{useful}). Useful energy is defined as energy with temperature above 45ºC.

2.3. 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 test is carried out with the collector loop disconnected, eliminating the possibility of reverse flow during the night.

The procedure aims to determine the heat loss coefficient U_s of the storage tank.

2. 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 (U_s), 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.

The solar fraction (f_{SOL}) is defined as the energy supplied by the solar part (Q_L) divided by the total system load (Q_D = heat demand).

$$f_{SOL} = \frac{Q_L}{Q_D} \quad \text{(eq. 3)}$$

3. Description of comparative analysis

In this section, a comparative analysis of some parameters [Performance without thermal loss (a_1/A), solar fraction f_{SOL}, tank heat loss coefficient (U_s) and useful energy for the degree of mixing test (Q_{useful})] obtained for different domestic water heating systems tested according to Standard ISO 9459-2 was done.

3.1. Testing samples

The following table describes the diferent analized systems.

Tab. 1: Systems characteristic

System number	Aperture Area *A* (m^2)	Tank volume *V* (l)	Insulation thickness (mm)	*V/A* (l/m^2)	Exchanger model	Exchanger area (m^2)	*Us* (W/K)
1	2.06	200	50	97.09	Tubular	0.45	3.66
2	4.12	320	50	77.67	Tubular	0.91	6.09
3	4	282	50	70.5	Tubular	0.90	4.25
4	2	187	50	93.5	Tubular	0.40	3.90
5	2.16	200	50	92.59	Double jacket	1.41	4.21
6	4.32	287	50	66.44	Double jacket	2.19	4.72
7	2.3	192	40	83.48	Double jacket	1.16	3.34
8	3.6	280	40	77.78	Double jacket	1.57	3.90
9	2	192	40	96	Double jacket	1.16	3.43
10	1.8	145	40	80.56	Double jacket	0.98	3.49

11	3.84	300	50	78.13	Double jacket	1.67	5.07
12	1.92	200	50	104.17	Double jacket	0.90	4.17
13	1.92	150	50	78.13	Double jacket	0.80	3.23
14	3.81	300	50	78.74	Double jacket	1.8	4.59
15	3.76	300	60	79.79	Double jacket	2.10	5.55
16	2.2	155	40-60	70.45	Double jacket	0.65	3.87
17	2.2	195	40-60	88.64	Double jacket	0.70	4.93
18	4.36	295	40-60	67.66	Double jacket	1.11	5.02

Table 1 shows like manufactures choose to sell systems with double jacket tanks.

3.2. Comparative analysis of performance without thermal loss (a_1/A) and solar fraction f_{SOL}.

In this section, a comparative analysis of systems performance is shown by calculating the performance without thermal loss (a_1/A) and solar fraction f_{SOL} in different reference locations (Stockholm, Würzburg, Davos and Athens) for different volume/area ratios. A comparative analysis of systems performance and solar fraction to different locations between tubular heat exchanger tanks and double jacket heat exchanger tanks is also shown.

3.3. Comparative analysis of tank heat loss coefficient (U_s).

In this section, different values obtained for the storage tank's heat loss coefficient (U_s) in funtion of tank volume (150, 200 an 300 l approximately) was compared.

3.4. Comparative analysis of useful energy for the degree of mixing test.

In this section, the useful energy (energy with temperature above 45ºC) for the degree of mixing in the storage tank during a draw-off test is determinated. In the Fig. 1, it can be observed the useful energy, Q_{useful}, and not useful energy, $Q_{not\ \mathrm{useful}}$, obtain for the degree of mixing test.

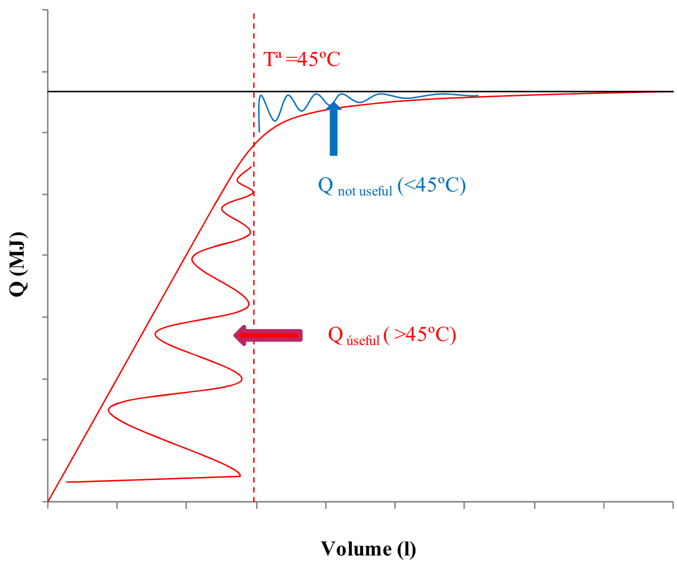

Fig. 1: *Q* vs Volume degree of mixing test

4. Comparative analysis

4.1. Comparative analysis of performance without thermal loss (a_1/A) and solar fraction f_{SOL}.

Figure 2 shows performance without thermal loss (a_1/A) and for different volume/area ratios. It can be seen that while the V/A ratios increase, the performance without thermal loss (a_1/A) increase too. A relation between performance without thermal loss (a_1/A) and V/A ratios can be determined and is given by:

$$\frac{a_1}{A} = 0{,}155 \cdot \frac{V}{A} + 34{,}515 \qquad \text{(eq. 4)}$$

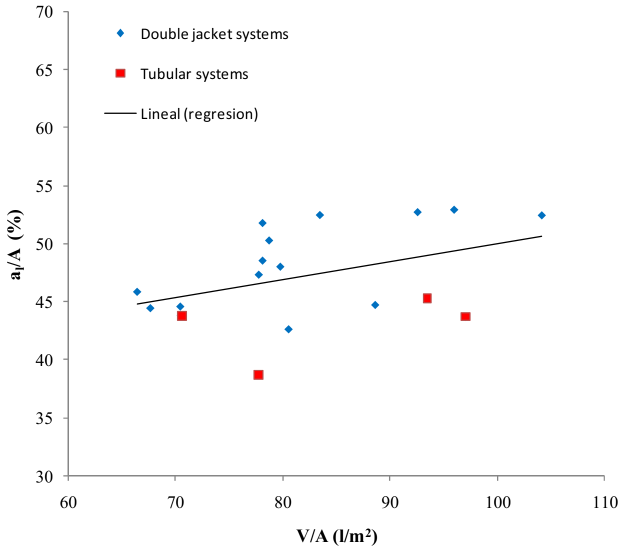

Fig. 2: a_1/A vs V/A

Figure 3 shows performance without thermal loss (a_1/A) of double jacket heat exchanger is higher than that of a tubular heat exchanger. A different of 3.9 % for values of *V/A* ratios about 70 and 5.6 % for values of *V/A* ratios about 100.

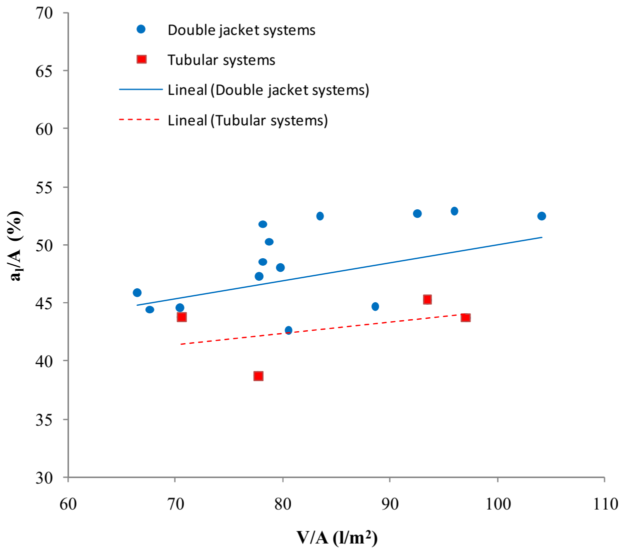

Fig. 3: a_1/A vs V/A

Figure 4 shows solar fraction (f_{SOL}) in different reference locations (Stockholm, Würzburg, Davos and Athens) for different volume/area ratios to 18 domestic water heating thermosiphon systems. It can be seen that while the *V/A* ratios increase, solar fraction decrease too. Also, solar fraction (f_{SOL}) of double jacket heat exchanger is higher than that of a tubular heat exchanger. A different of 0.2-0.3-1.5-0.9% for values of *V/A* ratios about 70 and 5.1-5.8-5.8-6.6 % for values of *V/A* ratios about 100 for locations in Stockholm, Würzburg, Davos and Athens respectively.

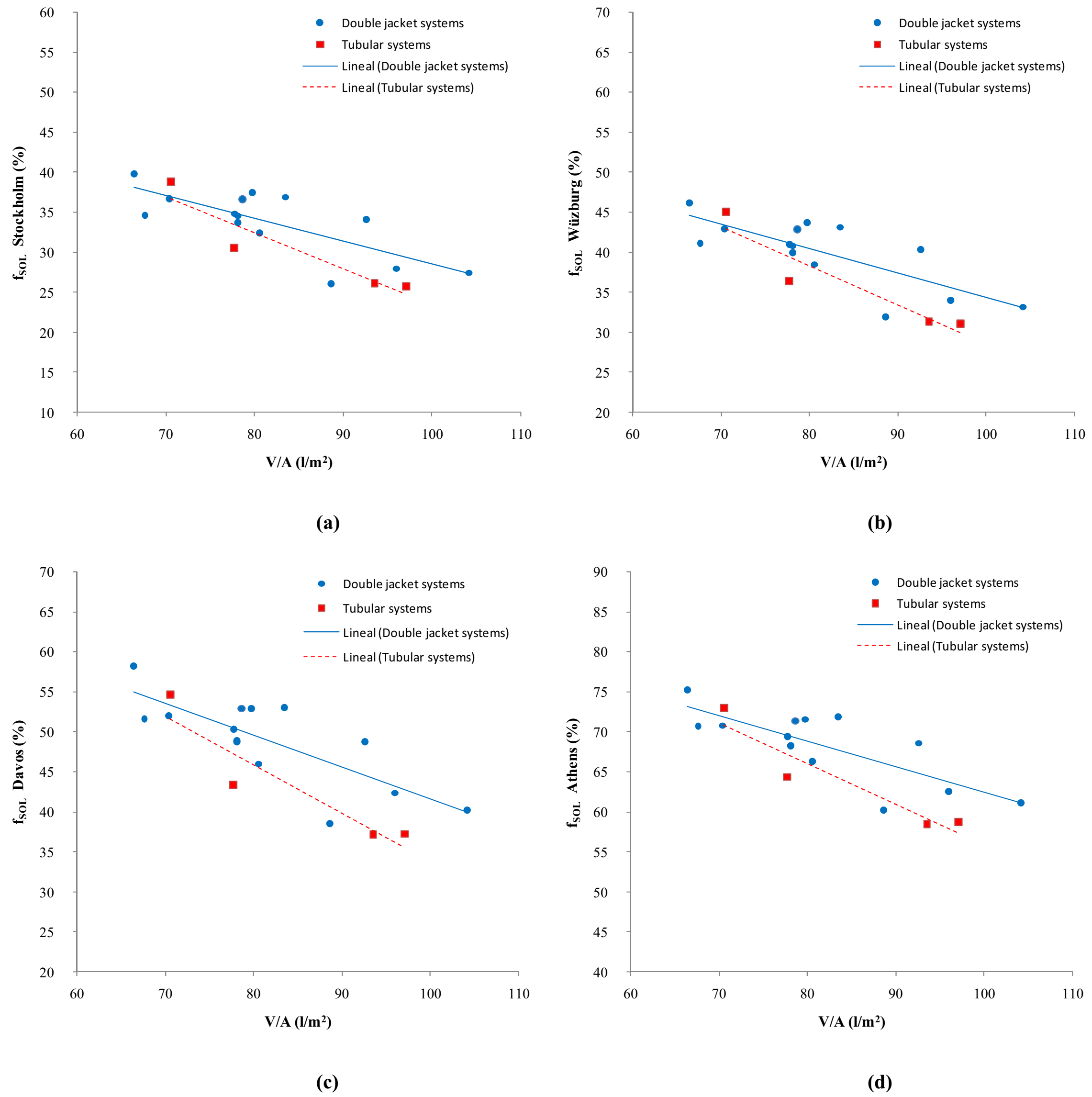

Fig. 4: f_{SOL} results (a) Stockholm (b) Wüzburg (c) Davos and (d) Athens

Figure 5 shows fitted lines solar fraction (f_{SOL}) in different reference locations (Stockholm, Würzburg, Davos and Athens) for different volume/area ratios.

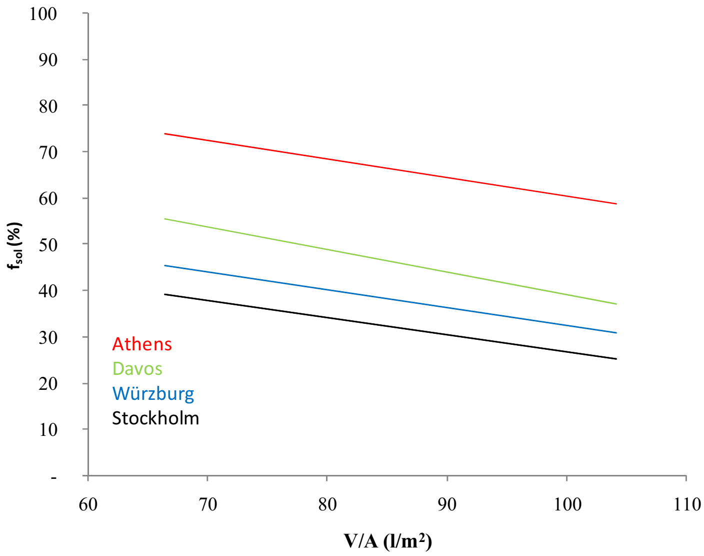

Fig. 5: f_{sol} results in different reference locations

A relation between solar fraction (f_{SOL}) and *V/A* ratios can be determined for different reference locations and is given by Eq. 5-8:

- Stockholm

$$f_{SOL,Stockholm} = -0{,}338 \cdot \frac{V}{A} + 60{,}894 \quad \text{(eq. 5)}$$

- Wüzburg

$$f_{SOL,Wüzburg} = -0{,}362 \cdot \frac{V}{A} + 68{,}884 \quad \text{(eq. 6)}$$

- Davos

$$f_{SOL,Davos} = -0{,}469 \cdot \frac{V}{A} + 86{,}234 \quad \text{(eq. 7)}$$

- Athens

$$f_{SOL,Athens} = -0{,}381 \cdot \frac{V}{A} + 98{,}689 \quad \text{(eq. 8)}$$

4.2. Comparative analysis of tank heat loss coefficient (U_s).

In Table 2, it can be seen the storage tank's heat loss coefficient summarize for different tank volume range (150, 200 and 300 l)

Tab. 2: Tank heat loss coefficient

Volume *V* (l)	U_s average (W/K)	U_s maximum (W/K)	U_s minimun (W/K)	U_s/V (W/ l*K)
300± 20 l	4.88	6.09	3.9	0.0165
200± 15 l	3.95	4.93	3.34	0.0202
150± 5 l	3.53	3.87	3.23	0.0235

From the analysis of the U_s/volume ratios, it can be observed that 300 l systems has 22,5% lower loss per storage mass unit than 200 l system, and this 16,3% lower than 150 l systems. This is due to the fact that the systems with higher volume, it has lower outside exchanger surface/volume ratio.

4.3. Comparative analysis of useful energy for the degree of mixing test.

Table 3 shows that useful energy values, Q_{useful} (45ºC), are between 60-87%. In the absence of a modulating thermostatic heater as auxiliary energy, it would be convenient higher Q_{useful} (45ºC) value, so it has greater quantity of water with temperature higher to 45ºC.

Tab. 3: Degree of mixing test results

System nº	Initial water temp. t_i (ºC)	Cold water supply temp. t_{main} (ºC)	Difference t_i-t_{main} (ºC)	Total energy extracted *Q* (MJ)	Useful energy Q_{useful} (MJ)	Ratio Q_{useful} / *Q* (%)
1	63.54	19.15	44.39	39.70	34.45	86.8
2	61.1	13.79	47.31	64.76	53.6	82.8
3	61.66	12.3	49.36	43.90	35.72	81.4
4	61.74	13.39	48.35	43.11	35.53	82.4
5	61.83	21.93	39.9	53.36	43.11	80.8
6	65.7	13.44	52.26	66.56	52.7	79.2

7	63.26	13.36	49.9	43.68	35.45	81.2
8	67.5	21.95	45.55	26.67	21.6	81.0
9	62.11	15.14	46.97	56.34	41.4	73.5
10	62.05	22.08	39.97	51.15	35.61	69.6
11	67.66	19.16	48.5	38.91	30.49	78.4
12	61.13	16.19	44.94	30.52	23.99	78.6
13	62	16.05	45.95	41.04	29	70.7
14	61.25	24.42	36.83	49.53	41.87	84.5
15	61.69	12.04	49.65	66.81	49.25	73.7
16	61.38	11.96	49.42	39.56	24.07	60.8
17	62.94	20.02	42.92	37.71	27.12	71.9
18	61.01	19.96	41.05	53.14	41.64	78.4

5. Conclusions

The conclusions of this work are summarized below:

The higher is the volume/area *V/A* ratio of the systems, the higher is performance without thermal loss (a_1/A) and also the lower is solar fraction (f_{SOL}).

Performance without thermal loss (a_1/A) of jacket double heat exchanger is higher than that obtained a tubular heat exchanger. A different of 3.9% for values of *V/A* ratios about 70 and 5.6 % for values of *V/A* ratios about 100.

Solar fraction (f_{SOL}) of jacket double heat exchanger is higher than that obtained a tubular heat exchanger. A different of 0.2-0.,3-1.5-0.9% for values of *V/A* ratios about 70 and 5.1-5.8-5.8-6.6 % for values of *V/A* ratios about 100 for locations in Stockholm, Würzburg, Davos and Athens respectively.

The higher tank volume, the lower loss per storage mass unit (U_s/Volume). 300 l systems has 22,5% lower loss per storage mass unit than 200 l system, and this 16,3% lower than 150 l systems.

The systems have a useful energy around 60-87% of the total energy of the tank in the degree of mixing in the storage tank test.

6. Nomenclature

Symbol	Quantity	Unit
A	solar field aperture area	m^2
a_1, a_2 and a_3	output characteristics of the system	
$f(V)$	normalized draw-off temperature profile	
f_{SOL}	solar fraction	
$g(V)$	normalized mixing draw-off temperature profile	
η	performance (-)	
t_i	initial water temperature.	ºC
t_{main}	cold water supply temperature.	ºC
Q	total energy extracted from the system.	MJ
Q_{useful}	useful energy with temperature above 45ºC.	MJ
U_s	storage tank heat loss coefficient	W/K
V	storage volume	l

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