View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Repositório do LNEG

Assessment of Durability of Solar Absorbers - Performance Criterion

Soraia Páscoa[1], Maria João Carvalho[1] and Teresa Cunha Diamantino[1]

[1] Laboratório Nacional de Energia e Geologia, I.P., Lisbon (Portugal)

Abstract

Solar fraction, F_s, defined as the ratio between the delivered energy from a solar domestic hot water (DHW) system and the load (thermal energy necessary to satisfy domestic water heating needs), is widely accepted as performance indicator for this type of systems. Considering solar absorptance α_s and thermal emittance ε_t as the most relevant characteristics of solar absorbers, the relation between the depreciation of these optical properties and depreciation of F_s was used by Hollands et al (1992) to define a performance criterion (PC) for assessment of long-term behavior and service life of selective solar absorbers. The PC was established mainly for solar DHW systems working with solar fractions lower than 50%. In this work, systems working with solar fractions higher than 50%, in climates of south of Europe, are considered and the suitability of solar fraction as performance indicator to develop an adequate PC is studied. As a first step simulations of thermal performance of systems using an in-house software were performed for a reduction of 5% and 10% of F_s. In ISO 22975-3, solar fraction F_s degradation must be lower than 5% to guarantee 25 years of service life for DHW system. The results showed that the parameters obtained to define the PC were incoherent considering solar fractions higher than 50%. In a second step, supplied energy was considered as performance indicator and using similar methodology as Hollands et al (1992), but using as performance indicator energy supplied by the solar system, the PC for systems working with solar fractions higher than 50%, in climates of south of Europe, was establish. The results showed that this is not significantly different from the PC considered in ISO 22975-3.

Keywords: Durability, Solar Absorbers, Performance Criterion

1. Introduction

Assessment of long-term behavior and service life of selective solar absorbers used in solar thermal collectors for domestic hot water (DHW) systems can be performed according to ISO 22975-3. The Performance Criterion used in the standard was establish considering that for a service life of 25 years, reduction in solar fraction F_s should not be higher than 5%. In the frame of Task X of the IEA Solar Heating and Cooling Programme (Carlsson, B. et al, 1994) and according to Hollands et al (1992) it was possible to establish a performance criterion given by the change in optical properties of solar absorbers, namely, solar absorptance, α_s, and thermal emittance, ε_t:

$$PC = -\Delta\alpha_s + 0.25\Delta\varepsilon_t \leq 0{,}05 \qquad \text{(eq.1)}$$

where $\Delta\alpha_s = \alpha_s - \alpha_{s0}$ and $\Delta\varepsilon_t = \varepsilon_t - \varepsilon_{t0}$, according to ISO 22975-3 (2014).

The selection of this expression was established assuming that this equation is representative of the degradation of solar absorber surfaces used in DHW systems with solar fractions lower than 50% and corresponds to a reduction of 5% of the solar fraction.

Latter, changes introduced by Köhl, M. et al (2004) conduct to the expression presently used in the standard:

$$PC = -\Delta\alpha_s + 0.50\Delta\varepsilon_t \leq 0{,}05 \qquad \text{(eq.2)}$$

and considered valid for collectors working at higher temperatures.

In this work the procedure for establishment of the performance criterion is revisited considering DHW systems working with higher solar fractions, in climates of the south of Europe. In section 2, the methodology proposed by Hollands et al (1992) was applied considering as performance indicator the Solar Fraction. In section 3, a different performance indicator, supplied energy, is used and deduced. In section 4. conclusions are presented.

2. Solar Fraction as performance indicator

2.1. Methodology

Considering different combinations of optical properties, through analytical expressions according to (D.E. Roberts and A. Forbes, 2012) it was possible to obtain the thermal performance coefficients η_0 (-), a_1 ($Wm^{-2}K^{-1}$) and a_2 ($Wm^{-2}K^{-2}$) for a flat plate collector whose constructive characteristics are known (see Tab. 1). Computer simulations of thermal performance of systems were performed, using an in house software (SolTerm, V5.3, 2017), in order to analyze the solar fraction (F_s) of DHW systems, with a collector area of 4.3 m^2 and storage volumes of 200 L (a), 250 L (b) and 300 L (c), located in Lisbon. These systems have different ratios between store volume and collector area, 46.5 L/m^2 (a), 58.1 L/m^2 (b) and 69.8 L/m^2 (c) respectively. In Tab. 1 are presented the assumed values of input parameters used in the analytical expressions and computer simulations. Symbols in Tab. 1 follow the nomenclature of D.E. Roberts and A. Forbes (2012) and the input parameters signaled with (*) are according with this reference.

Tab. 1: Assumed values of input parameters for computer simulation of thermal performance of system (a). (*) Input parameters according with (D.E. Roberts and A. Forbes, 2012)

Input parameter		Assumed value	Unit
G	Incident solar power	800 (*)	[Wm^{-2}]
A_c	Collector area	4.3	[m^2]
	Collector tilt angle	33°	
	Collector orientation	South-facing (*)	
	Tank volume	200	[L]
T_{sp}	Set point temperature	50 (*)	[°C]
	Heat exchanger effectiveness	0.55	
δ	Collector absorber plate thickness	0.0003	[m]
D	Diameter of tube	0.008	[m]
W	Distance between fins	0.125	[m]
τ	Cover plate transmission	0.885	
T_a	Ambient temperature	293.15	[K]
T_{in}	Inlet water temperature	288.15	[K]
h_b	Conduction heat loss coefficient through base	1.167	[$Wm^{-2}K^{-1}$]
L_b	Thickness of base insulation	0.030	[m]
k_b	Conductivity of insulation	0.035	[$Wm^{-1}K^{-1}$]
m	Total mass flow rate of fluid	0.02 (*)	[Kgs^{-1}]
C_b	Conductance of fin to plate bond	100 (*)	[$Wm^{-1}K^{-1}$]
σ	Stefan-Boltzman constant	5.6704×10^{-8}	[$Wm^{-2}K^{-4}$]
h_{fi}	Heat transfer coefficient fin to fluid	250 (*)	[$Wm^{-2}K^{-1}$]
h_0	Temperature independent convection heat loss coefficient, absorber to cover plate	3.07 (*)	[$Wm^{-2}K^{-1}$]
h_1	Temperature dependent convection heat loss coefficient, absorber to cover plate	0.0096 (*)	[$Wm^{-2}K^{-2}$]
h_2	Wind speed independent convection heat loss coefficient, cover plate to ambient	6.9 (*)	[$Wm^{-2}K^{-1}$]
h_3	Wind speed dependent convection heat loss coefficient, cover plate to ambient	3.87 (*)	[$Wm^{-3}sK^{-1}$]
V	Wind speed	2	[ms^{-1}]
k_c	Thermal conductivity of collector	385 (*)	
C_p	Specific heat of water	4190 (*)	[$JKg^{-1}K^{-1}$]
α_{s0}	Initial solar absorptance	0.96	
ε_0	Initial thermal emittance	0.11	

The methodology proposed by Hollands et al (1992) was also used. Fig. 1 illustrates the solar fraction F_s as a function of solar absorptance α_s and each curve corresponds to a fixed value of thermal emittance ε_t for situation (a). In this figure it is also possible to visualize which combinations of α_s and ε_t will produce a 5 and 10% loss in solar fraction, F_s. In this analysis the initial optical properties considered are $\alpha_{s0} = 0.96$ and $\varepsilon_0 = 0.1$, which characterized the initial status of the flat plate collector considered. The simulations considered combinations of 0.025 increments in solar absorptance α_s, from 0.1 to 0.96, and 0.1 increments in thermal emittance ε_t, from 0.11 to 1.

Two possible states of failure are considered when compared with the initial solar fraction F_{s0}, i.e., when $F_s = 0.90\ F_{s0}$ and $F_s = 0.95\ F_{s0}$, respectively. F_{s0} represents the solar fraction when the solar DHW system operates with $\alpha_s = \alpha_{s0}$ and $\varepsilon_t = \varepsilon_{t0}$. The combination values of α_s and ε_t that correspond to a reduction of 5% or 10% in the system solar fraction were determined from Fig. 1. The intersection between the horizontal lines and the curves of fixed ε_t for F_s versus α_s gives the combination of α_s and ε_t that will produce a 5 and 10% loss in solar fraction F_s. In Fig. 2, -$\Delta\alpha_s$ is represented as a function of $\Delta\varepsilon_t$ for the three systems considered, (a), (b) and (c).

From Hollands et al (1992), these results are highly influenced by geographical location. However, it is possible to see that they are not dependent on the variation of system configuration, i.e, the results are very similar when considering storage volumes of 200 L (a), 250 L (b) and 300 L (c) as can be seen in Fig. 2.

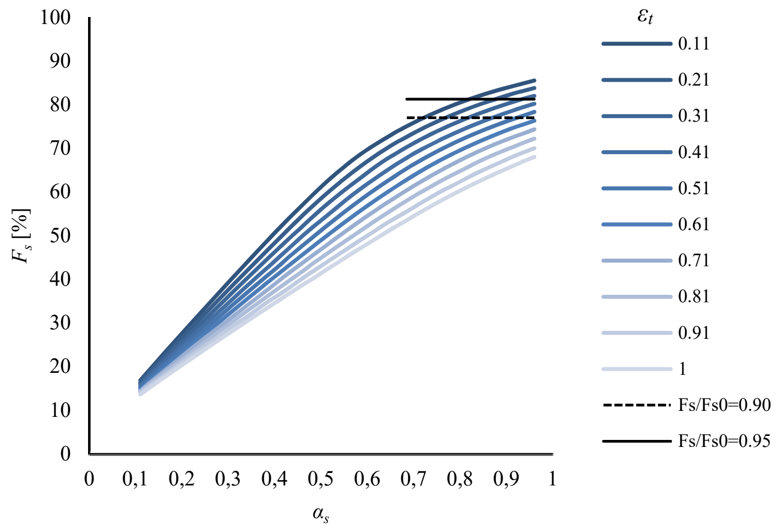

Fig. 1: Solar fraction as a function of α_s and ε_t for system (a) for a system located in Lisbon (latitude = 37.8°)

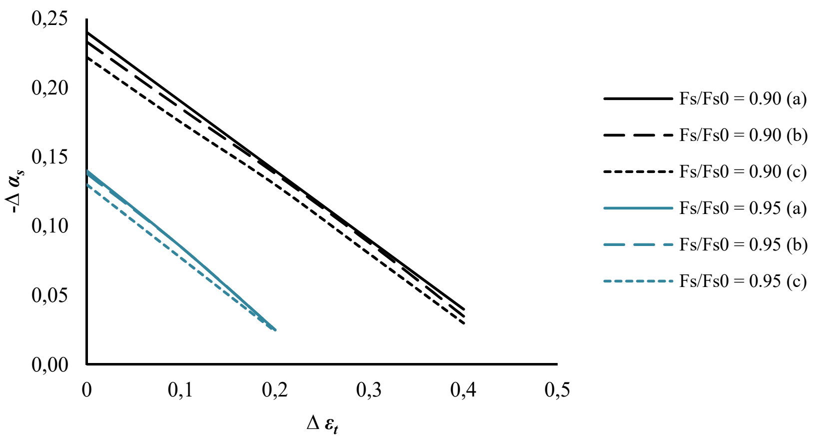

Fig. 2: $\Delta\alpha_S$ versus $\Delta\varepsilon_t$ for the three systems (a, b and c) considered for a system located in Lisbon (latitude = 37.8°)

The relationship between $\Delta\alpha_s$ and $\Delta\varepsilon_t$ is very close to linear, as already presented in Hollands et al (1992), which makes easier further interpretation of these graphs to determine which will be the adequate expression for PC considering solar fractions higher than 50% in climates of South of Europe.

Following the methodology proposed by Hollands et al (1992), $\Delta\alpha_s$ versus $\Delta\varepsilon_t$ can be expressed as:

$$-\Delta\alpha_s = a - \frac{a}{b}\Delta\varepsilon_t \qquad \text{(eq.3)}$$

When $\Delta\varepsilon_t$ is equal to zero, the parameter *a* is obtained (vertical intercept). When $\Delta\alpha_s$ is equal to zero, the parameter *b* is obtained (horizontal intercept).

The Eq. 3 can be transformed into

$$-\Delta\alpha_s + k_1\Delta\varepsilon_t = k_2 \quad \text{(eq.4)}$$

Where

$$k_1 = \frac{a}{b} \quad \text{(eq.5)}$$

$$k_2 = a \quad \text{(eq.6)}$$

Which gives a general form of the expression of PC presently used in the standard ISO 22975 (2014),

$$PC = -\Delta\alpha_s + k_1\Delta\varepsilon_t \leq k_2 \quad \text{(eq.7)}$$

2.2. Results

Considering the situation (a) in Fig.2, when and $F_s = 0.95\ F_{s0}$ we find $a = 0.14$ and $b = 0.24$ and, when $F_s = 0.90\ F_{s0}$ we find $a = 0.24$ and $b = 0.48$. The parameter *b* was calculated by determining the linear function that best fits each case, since it is not possible to directly obtain the horizontal intercept from Fig.2 ($\Delta\alpha_s = 0$).

According to Hollands et al (1992), if all solar radiation absorbed by the collector is converted in useful energy, i.e., is transferred to the load, a reduction of the solar fraction F_s will be proportional to a reduction on α_s, if all other parameters are unchanged, i.e., $\Delta\varepsilon_t = 0$. This meaning that, in Fig. 2, the vertical intercept (denoted by *a*) corresponding to $\Delta\varepsilon_t = 0$ would be $0.96 \times 0.05 = 0.048$ (for 5% reduction in solar fraction) or $0.96 \times 0.10 = 0.096$ (for 5% reduction in solar fraction) since $\alpha_{s0} = 0.96$.

The difference in *a* value determined based on the simulations and giving the linear representation of Fig. 2 and equations 3 to 6, can only be explained due to the fact that for higher solar fractions not all energy is transferred to load. There is dumped energy and the proportionality between a decrease in α_s and F_s can no longer be considered.

For higher solar fractions we have:

$$a = \Delta\alpha_{s0}|_{\Delta\varepsilon_t=0} > \alpha_{s0} \times \frac{\Delta F_S}{F_{S0}} \quad \text{(eq.8)}$$

or:

$$ratio = \frac{\frac{a}{\alpha_{s0}}}{\frac{\Delta F_S}{F_{S0}}} > 1 \quad \text{(eq. 9)}$$

Following Hollands et al (1992), the ratio (Eq. 9) versus F_s was analyzed taking into account all the simulations performed considering different ratios $\Delta F_s / F_{s0}$ for the DHW system studied in this work.

Tab. 2: Effect of the (arbitrarily-chosen) ratio F_s / F_{s0} on the vertical intercept *a* and ratio $(a / \alpha_{s0}) / (\Delta F_s / F_{s0})$

F_s / F_{s0}	$\Delta F_s / F_{s0}$	F_s	*a*	$(a / \alpha_{s0}) / (\Delta F_s / F_{s0})$
0.95	0.05	0.812	0.14	2.92
0.90	0.10	0.770	0.24	2.50
0.80	0.20	0.684	0.38	1.98
0.70	0.30	0.599	0.48	1.65
0.60	0.40	0.513	0.56	1.45
0.50	0.50	0.428	0.63	1.31
0.40	0.60	0.342	0.71	1.22
0.30	0.70	0.257	0.78	1.15
0.20	0.80	0.171	0.85	1.11

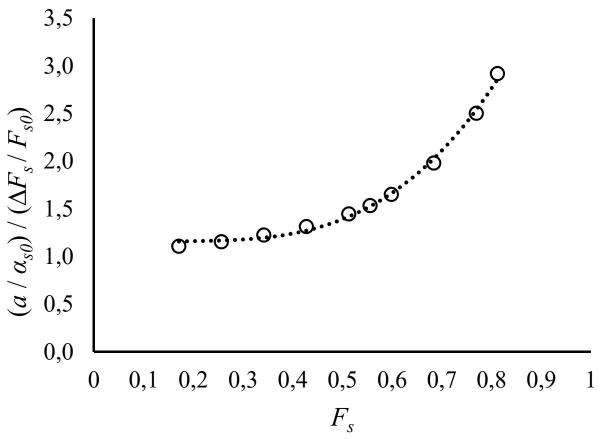

Fig. 3: Dependence of the ratio (a / α_{s0}) / (ΔF_s / F_{s0}) on F_s.

According to the results presented in Tab. 2, the proportionality between $\Delta\alpha_s$ and ΔF_s is clear at low solar fraction ($F_s < 0.5$) since the ratio (a / α_{s0}) / (ΔF_s / F_{s0}) shows a tendency to become constant and close to 1.1. Fig. 3 gives the dependence of the ratio (a / α_{s0}) / (ΔF_s / F_{s0}) on F_s and shows the same tendency for low solar fraction given by Hollands et al (1992).

According to Hollands et al (1992) and the above results, Eq. 10 shows the relationship between k_2 and a, given Eq. 6.

$$k_2 = a \approx \alpha_{s0} \times \frac{\Delta F_s}{F_{s0}} \times ratio \qquad \text{(eq.10)}$$

The performance criterion was determined for three different situations in order to meet the main objective of this study, i.e, the adequate expression for performance criterion considering solar fractions higher than 50% in climates of South of Europe. The results are presented in Tab. 3, 4 and 5. The parameter k_1 was calculated considering a and b, according to Eq. 5. The parameter k_2 was calculated considering α_{s0} = 0.96, the ΔF_s / F_{s0} and the respective ratio, according to Eq.10.

Firstly, the performance criterion was determined for low solar fraction considering an average value for all the solar fractions up to 50%, i.e. the average solar fraction between 20% and 50%, and then, compared with the performance criterion given by Hollands et al (1992). Secondly, the performance criterion was determined for solar fractions lower than 80%, considering an average value of all solar fractions from 20% up to 80%. Thirdly and last, the performance criterion was determined for a solar fraction equal to 80%, considering the ratio (a / α_{s0}) / (ΔF_s / F_{s0}) specific for that solar fraction.

For the first situation, shown in Tab. 3, for F_s / F_{s0} = 0.95, a = 0.14 and b = 0.24 are obtained and taking into account α_{s0} = 0.96 and ratio = 1.1 (low solar fraction), this leads to k_1 = 0.58 and k_2 = 0.05. The approximation $k2 \approx a$ was not found in this case. This also applies for F_s / F_{s0} = 0.90, where it is obtained a = 0.24 and b = 0.48, for the same α_{s0} and ratio, leading to k_1 = 0.50 and k_2 = 0.11, where k_2 is clearly different from a.

Tab. 3: Performance criterion for low solar fraction F_s < 0.5, considering an average value of all solar fractions up to 50%

F_s / F_{s0}	a	b	k_1	ratio (a / α_{s0}) / (ΔF_s / F_{s0})	k_2	PC
0.95	0.14	0.24	0.58	≈ 1.1	0.05	$PC = -\Delta\alpha_s + 0.58\Delta\varepsilon \leq 0.05$
0.90	0.24	0.48	0.50	≈ 1.1	0.11	$PC = -\Delta\alpha_s + 0.50\Delta\varepsilon \leq 0.11$

For the second situation, presented in Tab. 4, for F_s / F_{s0} = 0.95, a = 0.14 and b = 0.24 are also obtained and considering α_{s0} = 0.96 and ratio = 1.68 (solar fraction F_s < 0.8), this leads to k_1 = 0.58 and k_2 = 0.08. The approximation $k_2 \approx a$ was also not found in this case. This also applies for F_s / F_{s0} = 0.90, where it is obtained a = 0.24 and b = 0.48, for the same α_{s0} and ratio, leading to k_1 = 0.50 and k_2 = 0.16, where k_2 is different from a.

Tab. 4: Performance criterion for solar fraction F_s < 0.8, considering an average value of all solar fractions until 80%

F_s / F_{s0}	a	b	k_1	ratio (a / α_{s0}) / (ΔF_s / F_{s0})	k_2	PC
0.95	0.14	0.24	0.58	≈ 1.68	0.08	$PC = -\Delta\alpha_s + 0.58\Delta\varepsilon \leq 0.08$
0.90	0.24	0.48	0.50	≈ 1.68	0.16	$PC = -\Delta\alpha_s + 0.50\Delta\varepsilon \leq 0.16$

At last, for the third situation given by Tab. 5, for F_s / F_{s0} = 0.95, a = 0.14 and b = 0.24 are also obtained and considering α_{s0} = 0.96 and ratio = 2.76 (solar fraction F_s = 0.8), this leads to k_1 = 0.58 and k_2 = 0.13. The approximation $k_2 \approx a$ was found for this situation. For F_s / F_{s0} = 0.90, where it is obtained a = 0.24 and b = 0.48, for the same α_{s0} and ratio, leading to k_1 = 0.50 and k_2 = 0.26, where k_2 is quite close to a. This result is as expected, since the ratio used is obtained for higher solar fraction values.

Tab. 5: Performance criterion for solar fraction F_s = 0.8, considering the ratio corresponding to a solar fraction of 80%

F_s / F_{s0}	a	b	k_1	ratio (a / α_{s0}) / (ΔF_s / F_{s0})	k_2	PC
0.95	0.14	0.24	0.58	2.76	0.13	$PC = -\Delta\alpha_s + 0.58\Delta\varepsilon \leq 0.13$
0.90	0.24	0.48	0.50	2.76	0.26	$PC = -\Delta\alpha_s + 0.50\Delta\varepsilon \leq 0.26$

Although for higher solar fractions, values of k_2 and a are similar (Tab. 5), the PC obtained would correspond to a less demanding requirement, i.e., higher depreciation of α_s could be considered. Since collectors used in systems working at higher solar fractions are expected to work at higher temperatures, this less demanding requirement is not adequate, i.e., this methodology is unclear regarding to the suitability of the expression for performance criterion considering solar fractions higher than 50%.

3. Supplied energy as performance indicator

3.1. Methodology

It was decided to adopt another methodology in order to obtain more enlightening results. The methodology proposed by Hollands et al (1992) was also used but considering, as performance indicator, the supplied energy E of DHW system instead of solar fraction F_s. The initial supplied energy E_0 corresponds to the DHW initial state when $\Delta\alpha_s$ = 0 and $\Delta\varepsilon_t$ = 0.

When replacing the solar fraction F_s for supplied energy E, it was considered that supplied energy higher to Load was still useful energy. In this situation the depreciation in supplied energy is proportional do the depreciation in α_s which means a reduction of 5 or 10% in α_s that will cause a reduction of the supplied energy E.

Still following Hollands et al (1992) methodology, the ratio presented in Eq. 9 is transformed into Eq. 12, where the ratio versus E_0 was analyzed taking into account all the simulations performed considering different ratio E / E_0 for the DHW system studied in this work. Eq. 13 shows the relationship between k_2 and a, given Eq. 6.

$$ratio = \left(\frac{a}{\alpha_{s0}} / \frac{\Delta E}{E_0}\right) \qquad \text{(eq.12)}$$

$$k_2 = a \propto \alpha_{s0} \times \frac{\Delta E}{E_0} \times ratio \qquad \text{(eq.13)}$$

Similar to previous analysis, Fig. 4 illustrates the supplied energy E as a function of solar absorptance α_s and each curve corresponds to a fixed value of thermal emittance ε_t for situation (a). From this figure, combinations of α_s and ε_t that will produce a 5 and 10% loss in supplied energy are obtained. Two possible states of failure are represented when compared with the initial solar supplied energy E_0, i.e., when $E = 0.90\ E_0$ and $E = 0.95\ E_0$, respectively. E_0 represents the supplied energy when the DHW system operates with $\alpha_s = \alpha_{s0}$ and $\varepsilon_t = \varepsilon_{t0}$. In Fig. 5, $-\Delta\alpha_s$ is represented as a function of $\Delta\varepsilon_t$.

According to Eq. 12 and the results presented in Tab. 6, the proportionality between a and E_0 is evident for all supplied energies E and not only for a few situations has it happened (see Tab. 2 and Fig. 3) when solar fractions were used in the studied equations. The ratio (a / α_{s0}) / (ΔE_s / E_0) shows a tendency to become constant, particularly close to 1.1, for all supplied energies. Fig. 6 shows this dependence of the ratio on supplied energy E.

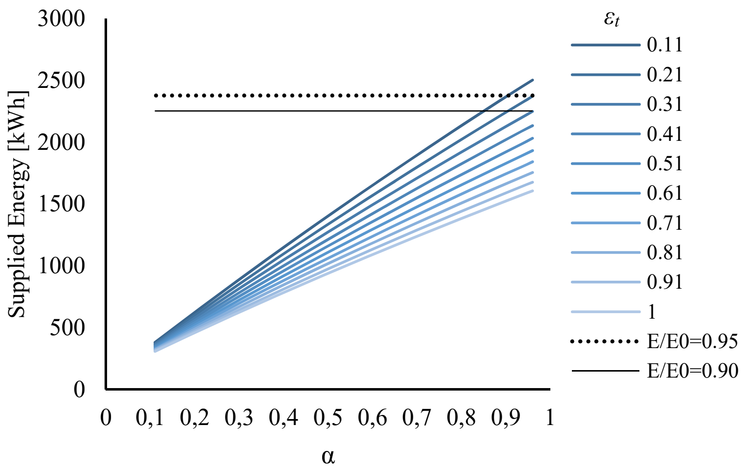

Fig. 4: Supplied energy as a function of α_s and ε_t and combinations of α_s and ε_t that will produce a 5% and 10% loss in the supplied energy of DHW system (a) located in Lisbon (latitude = 37.8°)

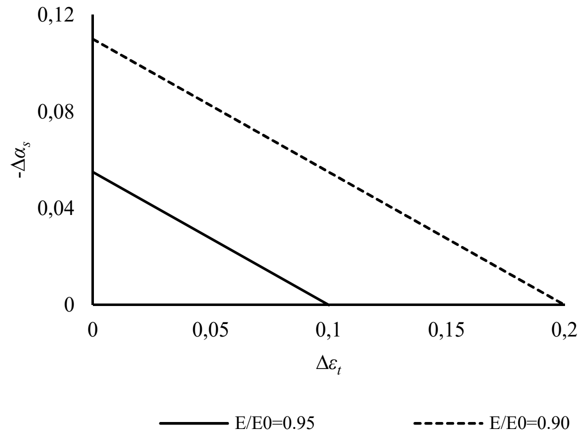

Fig. 5: Combinations of α_s and ε_t that will produce a 5% and 10% loss in the supplied energy of DHW system (a) located in Lisbon (latitude = 37.8°)

Tab. 6: Effect of the (arbitrarily-chosen) ratio E / E_0 on the vertical intercept a and ratio $(a / \alpha_{s0}) / (\Delta E / E_0)$

E / E_0	$\Delta E / E_0$	E	a	$(a / \alpha_{s0}) / (\Delta E / E_0)$
0.95	0.05	2378	0.14	1.15
0.90	0.10	2253	0.24	1.15
0.80	0.20	2002	0.38	1.12
0.70	0.30	1752	0.48	1.11
0.60	0.40	1502	0.56	1.10
0.50	0.50	1252	0.63	1.08
0.40	0.60	1001	0.71	1.07
0.30	0.70	751	0.78	1.06
0.20	0.80	501	0.85	1.05

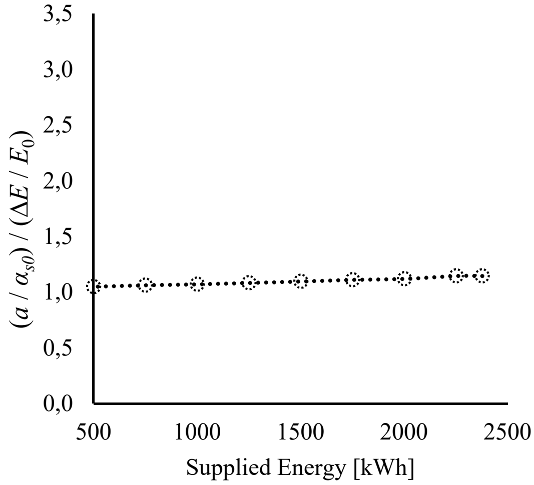

Fig. 6: Dependence of the ratio (a / α_{s0}) / (ΔE / E_0) on E.

3.2. Results

According to Tab. 6, for $E / E_0 = 0.95$, $a = 0.055$ and $b = 0.1$ were obtained and, considering $\alpha_{s0} = 0.96$ and ratio = 1.1, this leads to $k_1 = 0.55$ and $k_2 = 0.055$. The approximation $k_2 = a$ is clearly found in this situation. For $E / E_0 = 0.90$, $a = 0.11$ and $b = 0.2$ where obtained and, for the same α_{s0} and ratio, this leads to $k_1 = 0.55$ and $k_2 = 0.11$, where k_2 is equal to a.

Since the ratio (a / α_{s0}) / (ΔE_s / E_0) shows to be constant for all supplied energies, there is not a distinction between low or high supplied energy has it happens for solar fraction F_s. Then, the performance criterion given in Tab. 7 can be accept as a general equation. These results are consistent with the performance criterion given by ISO 22975-3:2014.

Tab. 7: Parameter k_1, k_2, ratio and performance criterion (PC)

E / E_0	a	b	k_1	ratio (a / α_{s0}) / (ΔE / E_0)	k_2	PC
0.95	0.055	0.100	0.550	≈ 1.1	0.055	$PC = -\Delta\alpha_s + 0.550\Delta\varepsilon \leq 0.055$
0.90	0.110	0.200	0.550	≈ 1.1	0.110	$PC = -\Delta\alpha_s + 0.550\Delta\varepsilon \leq 0.110$

4. Conclusions

In this work, solar DHW systems working with solar fractions higher than 50%, in climates of south of Europe, were considered. The suitability of solar fraction as performance indicator to develop an adequate PC was studied.

As a first step, simulations of thermal performance of systems using SolTerm software were performed for a reduction of 5% and 10% of F_s. According to Hollands et al (1992), if all solar radiation absorbed by the collector is converted in useful energy, i.e., is transferred to the load, a reduction of the solar fraction F_s will be proportional to a reduction on α_s, if all other parameters are unchanged, i.e., $\Delta\varepsilon_t = 0$. It was verified that this is only applicable for solar fraction lower than 50% and the results showed that the parameters obtained to define the PC were incoherent. For higher solar fractions, the PC obtained would correspond to a less demanding requirement, i.e., higher depreciation of α_s could be considered. Since collectors used in systems working at higher solar fractions are expected to work at higher temperatures, this less demanding requirement is not adequate, i.e., this methodology is unclear regarding to the suitability of the expression for performance criterion considering solar fractions higher than 50%.

In a second step, supplied energy was considered as performance indicator and using similar methodology as Hollands et al (1992), the PC for systems working with solar fractions higher than 50%, in climates of south of Europe, was establish.

When replacing the solar fraction F_s by supplied energy E, it was considered that supplied energy higher to load was still useful energy. In this situation the depreciation in supplied energy is proportional to the depreciation in α_s which means a reduction of 5 or 10% in α_s that will cause a reduction of the supplied energy E.

The results showed that the parameters used to define the PC are now not significantly different from the PC considered in ISO 22975-3.

The expression for performance criterion given by ISO 22975-3:2014 is adequate for solar fractions higher than 50% in climate of South of Europe.

5. Acknowledgments

The authors would like to thank to Doctor Nobumitsu Shohoji for valuable suggestions on the presentation of results of this work.

This work is a result of the project FCOMP-01-0124-FEDER-027507 (Refª FCT RECI/EMS-ENE/0170/2012) supported by Operational Competitiveness Programme (COMPETE) through the European Regional Development Fund (ERDF) and supported by FCT- Fundação para a Ciência e a Tecnologia, I.P. through National Funds and the project POCI-01-0145-FEDER-016709 (Refª FCT PTDC/EMS-ENE/0578/2014) supported by COMPETE 2020 and LISBOA 2020 under the PORTUGAL 2020 Partnership Agreement through the European Regional Development Fund (ERDF) and supported by FCT through National Funds.

6. References

K. G. T. Hollands, A. Karagiozis, A. P. Brunger, Effect of Selective surface degradation on the performance of solar water heating systems, Sol. Energy Mater. Sol. Cells 25 (1992) 125-141, https://doi.org/10.1016/0927-0248(92)90022-H

B. Carlsson, U. Frei, M. Köhl, K. Möller, Accelerated life testing of solar energy materials. Case study of some selective solar absorber coating materials for DHW-systems; A report of IEA Task X; Solar materials Research and development; SP Report 94:13; ISBN 91-7848-472-3 (http://ri.diva-portal.org/smash/record.jsf?pid=diva2%3A961896&dswid=-5275)

D. E. Roberts, A. Forbes, An analytical expression for the instantaneous efficiency of a flat plate solar water heater and the influence of absorber plate absorptance and emittance, Sol. Energy 86 (2012) 1416-1427, https://doi.org/10.1016/j.solener.2012.01.032

ISO 22975-3:2014, Solar Energy-collector components and materials – Part 3: Absorber surface durability, ISO 2014

ASTM G173 – 03, Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, 2012

SolTerm, LNEG, Version 5.3 – September 2017 (http://www.lneg.pt/iedt/projectos/370/)