DEVELOPMENT OF A SMALL-SIZED PARABOLIC-TROUGH COLLECTOR. FINAL CAPSOL PROJECT RESULTS

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Abstract

Small-sized parabolic-trough collectors, PTCs, are the concentrating solar system technology with the highest potential for thermal energy demand at temperatures up to 250ºC. The main applications in this temperature range are industrial process heat production, heat-powered refrigeration and cooling (especially double-effect absorption chillers) and low-temperature heat demand with high consumption rates (domestic hot water, space heating and swimming pool heating). A representative number of such facilities, mainly located in the United States, have been installed during the last three decades. Recently, private business and public institutions have shown a growing interest in this technology. The CAPSOL project undertakes the design, construction and testing of an innovative small-sized PTC for temperatures up to 250ºC. Three Spanish partners are participating, the *Plataforma Solar de Almería,* PSA, the University of Almeria, and the company Composites y Sol S.L. The testing was done in a solar optical and thermal performance test facility, designed and erected at the PSA. After the development and assessment of a first prototype, CAPSOL-01, some improvements were made and a second prototype, CAPSOL-02, was developed and assessed. Commercial version of CAPSOL collector is already on the market. This paper focuses on the final results of this project.

Keywords: solar thermal energy, parabolic-trough collector, industrial process heat, absorption chiller, water heating.

1. Introduction

Thermal energy demand at temperatures up to 250ºC currently represents a relevant percentage of global thermal energy consumption. Small-sized parabolic-trough collectors, PTCs, are the concentrating solar system technology with the highest potential for this thermal energy demand. On one hand, these temperature requirements cannot be efficiently reached by conventional low-temperature collectors (flat plate collectors, compound parabolic concentrators or evacuated tubes). On the other hand, use of solar concentrating systems with high concentration ratios and high-temperatures absorbers would be unnecessarily expensive. All these applications have stronger solar field space constraints than concentrating solar power plants. Factories and commercial buildings today are usually located in industrial zones or estates where the price of land is expensive, so installing the solar field on rooftops should be a real possibility. Therefore, these PTCs should be modular, small (aperture width under 3 m), light-weight and, of course, low-cost.

The main applications in this temperature range are:

- Industrial process heat, IPH, production. According to the last statistic of the International Energy Agency, IEA, corresponding to year 2008, the main energy consumption worldwide –around 30%- was registered in industrial sector, followed by residential and transport sectors (IEA, 2010). In 2007, there were about 90 operating IPH solar thermal plants[1] with a total capacity of about 25 MW_{th} (35,000 m^2) worldwide (Vannoni et al., 2008).

- Low-temperature heat demand with high consumption rates. One of the most widespread applications of solar thermal energy is hot water production. According to an IEA report for 2009, solar thermal collector capacity in operation worldwide equaled 172.4 GW_{th} (182.5 millions m^2), most of it for domestic hot water (kitchen, shower, laundry and sanitation facilities), space heating and swimming pool heating (Weiss and Maunthner, 2011).
- Heat-powered refrigeration and cooling, especially double-effect absorption chillers. The energy demand associated with air-conditioning in most industrialized countries has been increasing noticeably in recent years, causing peaks in electricity consumption during hot weather and disturbing the transport and distribution grid (Henning, 2007).
- In addition, organic Rankine cycle power plants, pumping irrigation water and desalination are also interesting applications that required thermal energy in this temperature range.

A representative number of facilities for the above mentioned applications, mainly for IPH applications, have been fed with PTC solar plants during the last three decades (Fernández-García et al., 2010a). Most of the facilities are located in the United States, although some have lately been built in other countries. Recently, private business and public institutions have shown a growing interest in this technology. However, at present only a few companies market PTC for such applications (Dudley, 1995; Lokurlu, 2005; Millioud and Dreyer, 2008), while a number of prototypes are also under development (Schwarzer et al., 2008; Weiss and Rommel, 2008).

The CAPSOL project undertakes the design, construction and testing of an innovative small-sized PTC for temperatures up to 250ºC (Fernández-García et al., 2010b). The project started in May 2008 and finished on December 2010 with funding from the Spanish Ministry of Science and Innovation. Three Spanish partners are participating, the PSA, the University of Almeria, and the company Composites y Sol S.L. The testing was done in a solar optical and thermal performance test facility, designed and erected at the PSA for accurate testing of small-sized PTCs, under real ambient conditions. Two collector prototypes, called CAPSOL-01 and CAPSOL-02, were successfully manufactured and tested. Commercial version of CAPSOL collector is already on the market. This paper focuses on the final results of this project.

2. Methodology

This section presents methodology followed in the design and construction of CAPSOL prototypes. Test facility erection is also briefly described.

2.1 Collector Design

The first step was to establish all specifications and requirements that the PTC must accomplish to have a proper solar collector. The following specifications were taken into account in the design process: modularity, small size, lightweight, easy installation and operation, minimal maintenance, durability in outdoor conditions, high overall efficiency, and low cost.

The thermal behavior of different trough designs with the same basic geometric characteristics was analysed and compared in detail using Fluent software for numerical simulation (Fernández-García et al., 2008). Results of the comparison using numerical simulation gave overall heat loss coefficients and temperature profiles.

The small PTC size allows a flat transparent cover (usually glass) to be added in the aperture plane. Such a cover improves structural stability, simplifies and reduces maintenance and cleaning operations, while also protecting the rest of the components from weathering, thereby increasing their durability. Therefore, the thermal effect of including a flat glass aperture cover was emphasized in the simulation study.

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[1] China and Japan not included

Three different trough designs were studied. Two of these designs had glass-tube covered receivers, one with an additional flat glass cover in the aperture plane and the other without it. The third design had a non-covered receiver and a flat glass cover in the aperture. The effect of installing thermal insulation on the back of the reflector was also studied in the designs with a flat-glass aperture cover. In addition, effects of trough inclination was analysed in one of the design. Conclusions were the following:

- The collector design with a single flat-glass aperture cover has the highest overall heat loss coefficient.
- The collector design with flat-glass aperture and tube covers has a lower overall heat loss coefficient than the collector design with a single glass-tube cover.
- It is suitable to incorporate a thermal insulation on the reflector back.
- Collector inclination was found to be of nearly negligible importance to thermal behaviour.

If both technical advantages and theoretical simulation results are accounted for, a collector with a flat-glass cover placed on the aperture plane and a non-evacuated glass tube surrounding the steel absorber tube was considered the most suitable option, in general; and specifically appropriate for a very dusty environment. Therefore, this design was selected for CAPSOL PTC (see figure 1). Absorber tube is placed at the rotation axis, thus avoiding flexible connections.

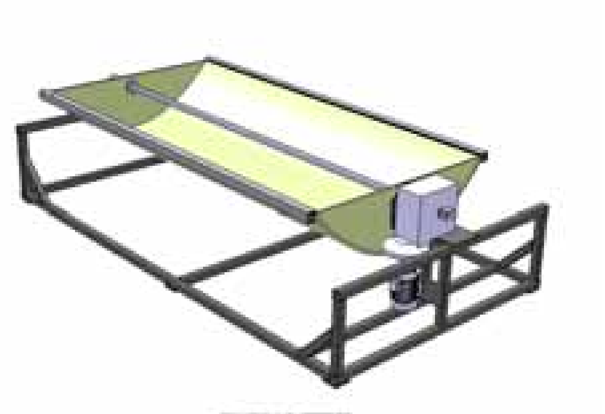

Figura 1. Scheme of the selected geometrical configuration for CAPSOL collector

The final main geometric parameters, some of them established taking into account standard sizes of commercial components, are given in Table 1.

Table 1. Main geometric parameters of the CAPSOL PTC

Parameter	Value
Aperture width (m)	1.0
Total length (m)	2.0
Focal length (m)	0.2
Rim angle (º)	102.7
Acceptance angle (º)	2.0
Outer steel absorber diameter (mm)	18.0
Flat-glass cover thickness (mm)	3.0
Geometric concentration ratio	17.7

Heat transfer fluid, HTF type (thermal oil or pressurized water), operating conditions (temperature and fluid flow) and absorber tube material (carbon steel or stainless steal) were also theoretically analysed in the selected design with Fluent to optimize the operating conditions. The fluid flow required to achieve a level of useful power is lower with water than with thermal oil. Therefore, the temperature increase per length unit obtained at certain useful power is higher with pressurized water and this was the selected HTF. Despite the fact that thermal conductivity of carbon steel is three times higher than the one of stainless steal, heat losses power is very similar using both and stainless steel was finally used for practical reasons.

A theoretical model to calculate the incidence angle modifier was also developed in Matlab environment. Lateral covers included in collectors with a flat glass cover to enclosure it produce a large shadowing at large incidence angles. Therefore, this model is specially focused on this effect.

2.2 Collector Manufacturing

A market study was done to look for components which comply with the established technical specifications. The following commercial components were bought:

- The reflector is a 0.5-mm aluminium sheet with a special solar coating, Mirosun by Alanod Solar.
- The absorber tube is stainless steel with selective coating of black Chrome, by Energie Solaire. Projects partners are currently studying the possibility of manufacturing an absorber tube with selective coating to reduce the cost and improve optical and thermal properties.
- Covers are made of low-iron glass without AR-coating. Future versions will include AR-coated glass covers.

Optical and thermal properties of these components are given in Table 2. Optical properties are solar-weighted.

Table 2. Optical and thermal properties of the selected commercial components

Parameter	Reflector	Covers	Absorber
Absorptance, α (%)	---	---	94.0
Specular reflectance, ρ (%)	88.0	---	---
Hemispherical transmittance, τ (%)	---	91.0	---
Emittance, ε (%) [at ambient temperature]	---	---	0.07

Project partners have developed and manufactured those components that were not found on the market. The need for a lightweight, rigid PTC led to use a composite structure material for the concentrator manufacturing. Aluminum reflector was attached to the concentrator inside surface during the manufacturing process. The low thermal conductivity of this composite material is equivalent to a thermal insulation on the reflector back, thus significantly reducing thermal losses, as was concluded in the theoretical study (see previous section). Additionally, a solar reflector was attached to the inside surface of both lateral covers to minimize the effect of the incidence angle.

The high optical-performance, pressure and temperature requirements to be met under any weather conditions throughout its long life cycle have made very strict detailed manufacturing and assembly procedures and processes necessary, beginning in the design, manufacturing and detailed geometrical checking of the concentrator moulds and ending in installation of seals, joints and rotating devices. As a conclusion, it was achieved a highly efficient, reliable and easy-to-maintain collector with a very reasonable and competitive cost.

The collector is provided with a one-axis sun tracking system that was previously developed at the PSA for other solar concentrating systems and especially adapted to CAPSOL PTC. This system calculates the Sun position by mean of a mathematical algorithm (Blanco-Muriel et al., 2001) and the collector position by using a magnetic band and a magnetic sensor that is located on collector axis. The resolution of the PSA sun tracker is currently below 0.05º (García, 2007).

Two units of the first collector prototype, called CAPSOL-01, were manufactured in summer 2008. After its assessment at the PSA, several improvements were detected and two units of the second prototype, called CAPSOL-02, were manufactured in autumn 2009. This new prototype includes the following modifications to improve the quality:

- The concentrator intercept factor (the portion of direct solar radiation reflected in the concentrator that reaches the receiver), γ, was increased, thanks to a photogrammetric study (Fernández-Reche and Fernández-García, 2009).
- The absorber tube alignment and positioning were improved by using a more accurate method.
- Water tightness was improved by modifying the flat-cover frame and the join elements between absorber tube and concentrator.
- New combinations of composite materials were applied, achieving a stronger, lighter and cheaper concentrator.

CAPSOL-02 was installed in spring 2010 at the PSA and assessed during that year. Figure 2 show pictures of CAPSOL-01 (left) and CAPSOL-02 (right).

Figure 2. CAPSOL prototypes installed at the PSA: CAPSOL-01 (left) and CAPSOL-02 (right)

2.3 Definition of Efficiency Parameters

Equations (1) to (4) are added to define the PTCs efficiency parameters. Overall efficiency in a solar collector, $\eta_{overall}$, is the ratio of useful thermal power transferred to the working fluid, $\dot{Q}_{useful}$ [W], to solar radiation power incident on the collector, $\dot{Q}_{solar}$ [W].

$$\eta_{overall} = \frac{\dot{Q}_{useful}}{\dot{Q}_{solar}} \quad (1)$$

Equation (2) expresses the useful thermal power as the difference between thermal power gained by the absorber tube, $\dot{Q}_{gain}$ [W], and thermal power lost to the ambient, $\dot{Q}_{loss}$ [W].

$$\dot{Q}_{useful} = \dot{Q}_{gain} - \dot{Q}_{loss} \text{ [W]} \quad (2)$$

Equation (3) is the common expression for PTC overall efficiency, by which thermal power gained is equal to direct solar radiation power multiplied by optical-geometrical efficiency, $\eta_{opt\text{-}geo}$.

$$\eta_{overall} = \eta_{opt-geo} - \frac{\dot{Q}_{loss}}{\dot{Q}_{solar}} \quad (3)$$

The optical-geometrical efficiency varies with angle of incidence of the incoming direct solar radiation, Θ [º], so it can be expressed by the product of its normal value (at Θ=0º, subscript $_{0º}$), $\eta_{opt\text{-}geo,0º}$, and the incidence angle modifier, $K(\Theta)$.

$$\eta_{opt-geo} = \eta_{opt-geo,0^\circ} \cdot K(\Theta) \quad (4)$$

Overall efficiency is obtained by equation (5), with two possibilities, expressing thermal lost to the ambient as thermal power losses, $\dot{Q}_{loss}$ [W], or as thermal efficiency, $\eta_{thermal}$.

$$\eta_{overall} = \eta_{opt-geo,0^\circ} \cdot K(\Theta) - \frac{\dot{Q}_{loss}}{\dot{Q}_{solar}} = \eta_{opt-geo,0^\circ} \cdot K(\Theta) \cdot \eta_{thermal} \quad (5)$$

Therefore, efficiency parameters that have to be calculated are: $\eta_{opt\text{-}geo,0º}$, $K(\Theta)$ and $\dot{Q}_{loss}$ [W] *or* $\eta_{thermal}$.

2.4 Test Facility

A solar thermal test facility was designed and erected at the PSA for accurate performance testing of small-sized PTCs, under real ambient conditions (Fernández-García et al., 2008). The HTF is pressurized water. The facility was designed to operate in a wide range of temperatures (from ambient to 235ºC), flow rates (up to 0.075 kg/s) and operating pressures (from 1 to 30 bar), and to test different collector sizes and axis orientations. CAPSOL prototypes were East-West oriented. Very accurate instruments were installed, in particular, flow meters, pyrheliometer and temperature sensors, to allow high quality PTCs assessment. Measured values are stored every 5 seconds in the database. Figure 3 shows a picture of the test facility designed to determine representative PTC parameters.

Figure 3. Solar thermal test facility for small-sized PTC at the PSA

Experimental procedures used to calculate efficiency parameters are:

- Peak optical-geometrical efficiency, $\eta_{opt\text{-}geo,0º}$. The working fluid is kept at ambient temperature to avoid thermal losses. The test is done around solar noon to minimize Θ.
- Incidence angle modifier, $K(\Theta)$. Working fluid is kept at ambient temperature, but testing is done over a long period of time along the day to cover a wide range of incidence angles. Θ .
- Thermal efficiency, $\eta_{thermal}$. The collector inlet temperature is kept at a given value and the test is performed around solar noon to minimize Θ. This test is done at several collector inlet temperatures throughout the operating range.

To assure quasi-steady state conditions, only tests with low fluctuations in ambient variables and operating parameter during the testing period were considered valid.

This solar thermal test facility also allows analyzing technical aspects of the tested collectors under real operating conditions, such as, materials durability, structural resistance, components assembly, etc.

3. Results and Discussion

Two complete test campaigns were carried out to assess two units of both prototypes, CAPSOL-01 and CAPSOL-02. All tests were done in the PSA test facility showed in fig. 3, following the experimental procedure described in the previous section.

Before starting the test campaigns, a specific experiment was done to determine the time constant. As the time constant obtained for this collector is around 1 minute, it was considered that a proper testing period for efficiency tests was 10 minutes. Results are presented as the average value during the testing period and the uncertainty associated, considering statistical and instrumental uncertainties. This section presents all experimental results obtained in the two test campaigns.

3.1 Peak optical-geometrical efficiency, $\eta_{opt\text{-}geo,0^o}$

From a theoretical point of view, this parameter can be split into terms for single physical effects: specular reflectance of the reflector, ρ, transmittance of the covers, τ_{tube} and τ_{flat}, absorptance of the absorber, α, intercept factor, γ, and the cleanliness and durability factor, F_{c+d}. In equation (6) the subscript 0^o means the parameters are defined at $\Theta = 0^o$.

$$\eta_{opt-geo,0^o} = \tau_{flat,0^o} \cdot \rho_{0^o} \cdot \tau_{tube,0^o} \cdot \alpha_{0^o} \cdot \gamma_{0^o} \cdot F_{c+d,0^o} \qquad (6)$$

The nominal values of the four firsts parameters are in table 2. γ obtained with photogrammetry was 92.3% for CAPSOL-01 and 96.5% for CAPSOL-02 (Fernández-Reche and Fernández-García, 2009). F_{c+d} is supposed to be equal to 1 when the collectors are fully clean. Substituting these values in equation (6), theoretical values calculated for both prototypes are showed in the first column of table 3. The increase in the second prototype value is only due to the better γ.

Table 3. Theoretical and experimental results of $\eta_{opt\text{-}geo,0^o}$ of CAPSOL-01 and CAPSOL-02

Prototype	Theoretical $\eta_{opt\text{-}geo,0^o}$ (%)	Experimental $\eta_{opt\text{-}geo,0^o}$ (%)
CAPSOL-01	63.2	66 ± 3
CAPSOL-02	66.1	62 ± 3

Figure 4 shows results obtained during several $\eta_{opt\text{-}geo,0^o}$ tests, both for CAPSOL-01 (Figure 4 left) and CAPSOL-02 (Figure 4 right), where ΔT [ºC] is the difference between the average fluid temperature, $T_{av,fluid}$ [ºC], and the ambient temperature, T_a [ºC]. Experimental data were fitted by using least mean squares method (red line in figures 4 left and right). Fitted values are included in the second column of table 3.

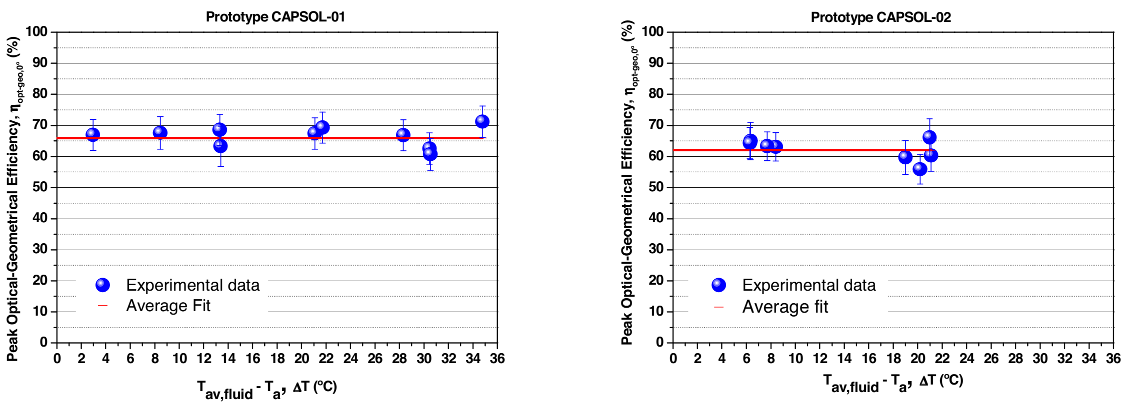

Figure 4. Experimental results of $\eta_{opt\text{-}geo,0^o}$ of CAPSOL-01 (left) and CAPSOL-02 (right)

As can be deduced from table 3 and figure 4, theoretical and experimental results of $\eta_{opt\text{-}geo,0^o}$ for CAPSOL-01 are rather similar, considering experimental uncertainties. However, experimental results of $\eta_{opt\text{-}geo,0^o}$ for

CAPSOL-02 are quite lower than those expected, according to theoretical results and comparing with experimental results for CAPSOL-01. After a detailed study about possible reasons of this decrease in the $\eta_{opt\text{-}geo,0^o}$ for the second prototype, a degradation in the selective coating of the steel absorber tube (and a reduction in α as a consequence) was considered as the most probable option.

3.2 Incidence angle modifier, K(Θ)

Figure 5 left shows the results obtained during two *K(Θ)* tests with CAPSOL-01 and Figure 4 right presents the results of two *K(Θ)* tests with CAPSOL-02. All tests were done during the whole day to compare morning and afternoon results.

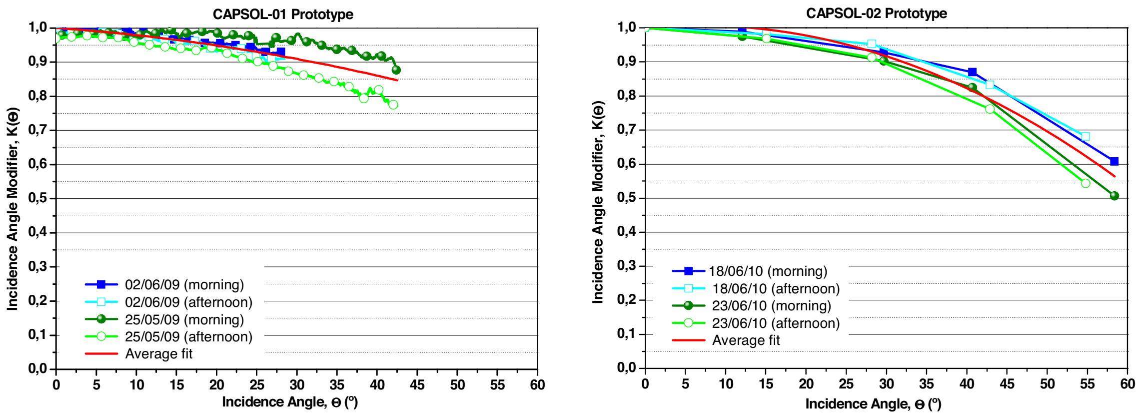

Figure 5. Experimental results of *K(Θ)* for CAPSOL-01 (left) and CAPSOL-02 (right)

Experimental data were fitted by using least mean squares method (red line in figure 5 left and right). Fitted values for CAPSOL-01 and CAPSOL-02 are included in expressions (7) and (8), respectively.

$$K(\Theta))_{CAPSOL-01} = 1 - (1{,}630 \pm 0{,}013) \cdot 10^{-3} \cdot \Theta - (4{,}64 \pm 0{,}04) \cdot 10^{-5} \cdot \Theta^2 \quad R^2 = 0{,}9999 \qquad (7)$$

$$K(\Theta))_{CAPSOL-02} = 1 + (22 \pm 7) \cdot 10^{-4} \cdot \Theta - (16{,}5 \pm 1{,}4) \cdot 10^{-5} \cdot \Theta^2 \quad R^2 = 0{,}9995 \qquad (8)$$

Both average curves are included in figure 6 to be easily compared. This graph is represented only up to *Θ*=40° because no higher values were tested with CAPSOL-01. As can be seen, *K(Θ)* for both prototypes are similar, because no changes affecting this parameter *K(Θ)* were introduced in the second prototype.

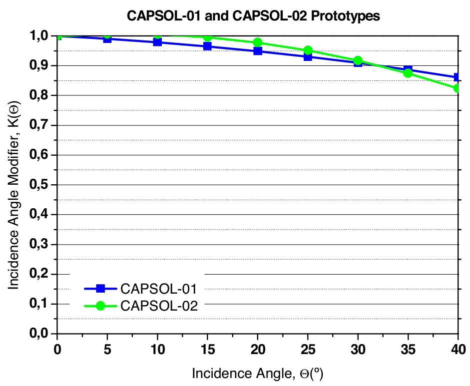

Figure 6. Comparison of average fit of *K(Θ)* for CAPSOL-01 and CAPSOL-02

Despite solar reflector were installed in the inside surface of the lateral covers, reducing the end losses, the effect of *Θ* is still very large, due to the shading of the initial lateral cover. However, in a commercial plant this effect will be less significant because collectors will be tilted and North-South oriented.

3.3 Overall efficiency, $\eta_{overalll}$

Thermal efficiency tests were done with both prototypes. Results are presented together with peak optical-efficiency ones (i.e., overall efficiency for a temperature difference equal to 0) for a clearest exposition. Figure 7 shows results of $\eta_{overall}$, both for CAPSOL-01 (Figure 7 left) and CAPSOL-02 (Figure 7 right).

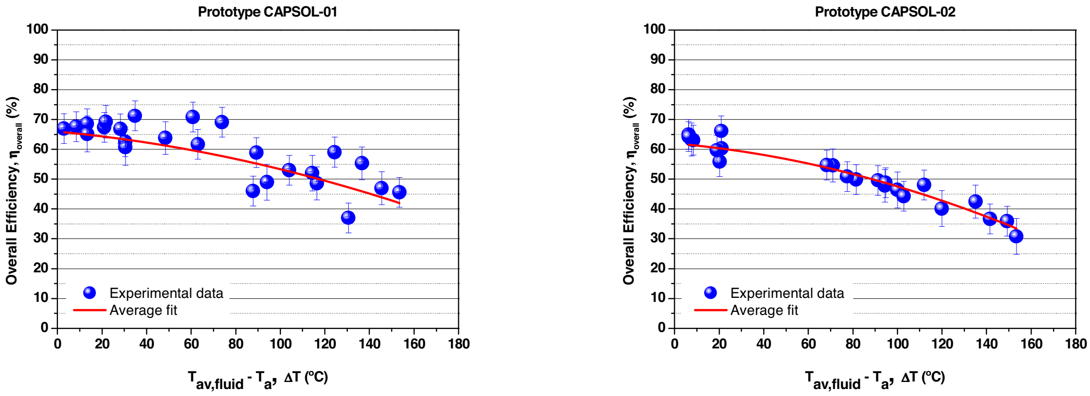

Figure 7. Experimental results of $\eta_{overall}$ for CAPSOL-01 (left) and CAPSOL-02 (right)

Experimental data were fitted by using least mean squares method (red line in figure 7 left and right). Fitted values for CAPSOL-01 and CAPSOL-02 are contained in expressions (9) and (10), respectively.

$$\left.\eta_{overall}\right)_{CAPSOL-01} = (66 \pm 3) - (7 \pm 5) \cdot 10^{-2} \cdot \Delta T - (6 \pm 4) \cdot 10^{-4} \cdot \Delta T^2 (\%) \qquad (9)$$
$$R^2 = 0{,}6704$$

$$\left.\eta_{overall}\right)_{CAPSOL-02} = (62 \pm 3) - (6 \pm 3) \cdot 10^{-2} \cdot \Delta T - (8 \pm 2) \cdot 10^{-4} \cdot \Delta T^2 (\%) \qquad (10)$$
$$R^2 = 0{,}9326$$

Both average curves are included in figure 8 to be easily compared. As can be seen, CAPSOL-02 curve is slightly lower than CAPSOL-01 one. The reason of this decreasing could be the degradation of the receiver tube selective properties along the time. This degradation could have affected not only to absorptance values (producing a lower peak optical-geometrical efficiency) but also to emittance values because the difference between both overall efficiency curves increases with the test temperature (see figure 8).

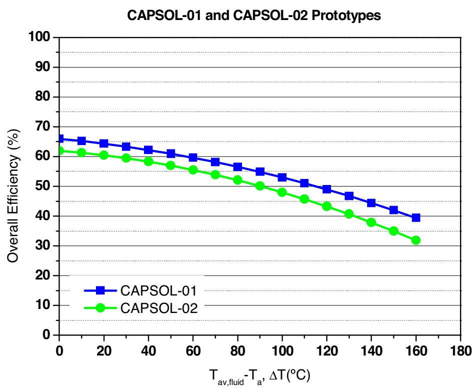

Figure 8. Comparison of average fit for $\eta_{overall}$ of CAPSOL-01 and CAPSOL-02

4. Conclusions

A new small-sized PTC for applications requiring thermal energy at temperatures up to 250ºC has been developed under the CAPSOL project. This is a very promising solar energy technology because it can be applied to many applications with high thermal energy consumption, especially industrial process heat production, heat-powered refrigeration and cooling and low-temperature heat demand with high consumption rates. A complete development of two prototypes, CAPSOL-01 and CAPSOL-02, including designing, manufacturing and testing, was successfully carried out. Although some improvements determined during the first-prototype assessment were included in the second prototype, overall efficiency of CAPSOL-02 is slightly lower, probably because degradation in the commercial receiver tube was suffered. To solve this problem, project partners are working on the development of a new receiver tube. The commercial version of CAPSOL collector is already available on the marked.

In addition, a new solar thermal facility has been erected and instrumented for testing of small sized parabolic troughs. Currently, this is the unique facility available in Spain for any company or institution that wants to check the thermal behaviour of its collector prototype with pressurized water (up to 30 bar) under real solar conditions.

List of Acronyms

PSA Plataforma Solar de Almería

PTC parabolic-trough collector

IPH industrial process heat

HTF heat transfer fluid

List of Symbols

α absorptance

γ intercept factor

ΔT difference between the average fluid temperature and the ambient temperature [ºC]

ε emittance

$\eta_{opt\text{-}geo}$ optical-geometrical efficiency

$\eta_{opt\text{-}geo,0^o}$ peak optical-geometrical efficiency

$\eta_{overall}$ overall efficiency

$\eta_{thermal}$ thermal efficiency

Θ incidence of the incoming direct solar radiation [º]

$K(\Theta)$ incidence angle modifier

ρ reflectance

τ transmittance

F_{c+d} cleanliness and durability factor

$\dot{Q}_{gain}$ thermal power gained by the absorber tube [W]

$\dot{Q}_{loss}$ thermal power lost to the ambient [W]

$\dot{Q}_{solar}$ solar radiation power incident on the collector [W].

$\dot{Q}_{useful}$ useful thermal power transferred to the working fluid [W]

T_a ambient temperature [ºC]

$T_{av,fluid}$ average fluid temperature [ºC]

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