EXPERIMENTAL ASSESSMENT OF A SMALL-SIZED PARABOLIC-TROUGH COLLECTOR. CAPSOL PROJECT

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Abstract

Thermal energy demand at temperatures up to 250ºC currently represents a significant percentage of global thermal energy consumption. The main applications that require thermal energy in this temperature range are industrial process heat production, heat-driven refrigeration and cooling (especially double-effect absorption chillers), low-temperature heat demand with high consumption rates, Organic Rankine Cycle (ORC) power plants, pumping irrigation water and desalination. Parabolic-trough collectors (PTCs) are the concentrating solar system technology with the highest potential for such demand. As a consequence of the growing interest in this technology, several companies and public institutions have recently marketed a number of commercial collectors and some prototypes are under development. This paper presents the experimental assessment of an innovative small-sized PTC for temperatures up to 250ºC, developed under the CAPSOL project. The testing was done in a solar optical and thermal performance test facility, designed and erected at the *Plataforma Solar de Almería* (PSA) for accurate testing of small-sized PTCs, under real ambient conditions. After the assessment of a first prototype, CAPSOL-01, some improvements were made and a second prototype, CAPSOL-02, was developed and is currently under assessment.

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 PTCs are the concentrating solar system technology with the highest potential for such demand. The main applications that require thermal energy at temperatures up to 250ºC are industrial process heat production, heat-driven refrigeration and cooling (especially double-effect absorption chillers), low-temperature heat demand with high consumption rates (domestic hot water, space heating and swimming pool heating), ORC power plants, pumping irrigation water and desalination. On one hand, these temperature requirements cannot be efficiently reached by conventional low-temperature collectors (flat plate collectors (FPC), compound parabolic concentrators (CPC) or evacuated tubes). On the other hand, use of solar concentrating systems with high concentration ratios and high-temperatures absorbers would be unnecessarily expensive.

These applications have stronger solar field space constraints than concentrating solar power (CSP) plants. Factories and commercial building 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.

Recently, private business and public institutions have shown a growing interest in this technology. However, at present only a few companies market collectors for such applications [1-3], while a number of prototypes are also under development [4, 5]. Most of the facilities are located in the United States, although some have recently been built in other countries [6].

The CAPSOL project undertakes the design, construction and testing of an innovative small-sized PTC for temperatures up to 250ºC [7]. The project started in May 2008, and is scheduled to last until December 2010 with funding from the Spanish Ministry of Science and Innovation. Three Spanish partners are participating, the PSA, the University of Almeria, and Composites y Sol S.L. This paper focuses on the experimental evaluation of the two collector prototypes, called CAPSOL-01 and CAPSOL-02, manufactured under the project.

2 Materials and Methods

2.1 Collector Design

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 behaviour of different trough designs with the same basic geometric characteristics was analysed and compared in detail using Fluent software for numerical simulation [8]. Results of th comparison using numerical simulation gave overall heat loss coefficients and temperature profiles.

The selected configuration has a flat glass cover placed on the aperture plane and a non-evacuated glass tube surrounding the steel absorber tube. This 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. The need for a lightweight, rigid PTC led to a composite structure with an aluminium reflector surface for the concentrator. Absorber tube is fixed, avoiding flexible connections.

The final main geometric parameters, some of them established taking into account standard sizes, 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 absorber diameter (mm)	18.0
Flat cover thickness (mm)	3.0
Geometric concentration ratio	17.7

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® from Alanod-Solar GMBH & Co. KG.
- The absorber tube is stainless steel with selective coating. 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.
- The covers are low-iron glass without AR-coating. Future prototypes will include AR-coated glass covers.

Optical and thermal properties of these components are given in Table 2. Optical properties are weighted with the solar spectrum.

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

	Reflector	Covers	Absorber
Absorptance (%)	---	---	94.0
Specular reflectance (%)	88.0	---	---
Hemispherical transmittance (%)	---	91.0	---
Emittance (%) [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 of a composite structure material for the concentrator manufacturing. 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. All of the above has achieved a very highly efficient, reliable and easy-to-maintain collector with a very reasonable and competitive cost. Additionally, a solar reflector was included in the inside surface of both lateral covers to minimize the effect of the incidence angle. The tracking method is a one axis system. It was previously developed at the PSA for other solar concentrating systems and has been especially adapted to CAPSOL PTCs. This system calculates the Sun position by mean of a mathematical algorithm 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.

Two units of the first prototype, called CAPSOL-01, were manufactured in summer 2008. After its assessment at the PSA (see section 3), several improvements was 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 was increased, thanks to a photogrammetric study [9].
- The absorber tube alignment and positioning were improved by using a more accurate method.
- 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 in the manufacturing process of CAPSOL-02, achieving a stronger, lighter and cheaper concentrator.

CAPSOL-02 was installed in spring 2010 at the PSA and its assessment will be finished by the end of 2010. Figure 1 show pictures of CAPSOL-01 (left) and CAPSOL-02 (right).

Figure 1. 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, P_{useful}, to solar radiation power incident on the collector, P_{solar}.

$$\eta_{overall} = \frac{P_{useful}}{P_{solar}} \quad (1)$$

Equation (2) expresses the useful thermal power as the difference between thermal power gained by the absorber tube, P_{gain}, and thermal power lost to the ambient, P_{loss}.

$$P_{useful} = P_{gain} - P_{loss} \quad (2)$$

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, $\eta_{opt\text{-}geo}$.

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

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

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

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

$$\eta_{overall} = \eta_{opt-geo,0^o} \cdot K(\varphi) - \frac{P_{loss}}{P_{solar}} = \eta_{opt-geo,0^o} \cdot K(\varphi) \cdot \eta_{thermal} \quad (5)$$

Therefore, efficiency parameters that it is necessary calculate are: $\eta_{opt\text{-}geo,0^o}$, $K(\varphi)$ and P_{loss} *or* $\eta_{thermal}$.

2.4 Test Facility

A solar thermal test facility has been designed and erected at the PSA for accurate performance testing of small-sized PTCs, under real ambient conditions [9]. The working fluid is pressurized water. The facility was designed to operate in a wide range of temperatures, flow rates and operating pressures, 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. Figure 2 shows a picture of the test facility designed to determine representative PTC parameters. Experimental procedures used to calculate efficiency parameters are:

- Peak optical-geometrical efficiency, $\eta_{opt\text{-}geo,0^o}$. The working fluid is kept at ambient temperature (to avoid thermal loss), and must be done around solar noon (to minimize the incidence angle).
- Incidence angle modifier, $K(\varphi)$. Working fluid is also kept at ambient temperature, but testing is done over a longer period during the day to include as many incidence angles as possible.
- Thermal efficiency, $\eta_{thermal}$. This performance test is done around solar noon and the collector inlet temperature must be kept at a given value. This test is done at several collector inlet temperatures throughout the operating range.

In addition, 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.

Figure 2. Solar thermal test facility for small-sized PTC at the PSA.

3 Results and Discussion

This section presents results of CAPSOL-01 prototype and some preliminary results of CAPSOL-02 prototype. The complete test campaign of CAPSOL-02 prototype will be finish by the end of 2010.

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, r, 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 zero incidence angle.

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

The nominal values of the four firsts parameters are in table 2. The intercept factor obtained with photogrammetry was 92.3% for CAPSOL-01 and 96.5% for CAPSOL-01 [15]. The cleanliness and durability factor is supposed to be equal to 1. Substituting these values in equation (6), theoretical values for $\eta_{opt\text{-}geo,0^o}$ of 63.2% and 66.1% are obtained for CAPSOL-01 and CAPSOL-02, respectively.

From the results obtained during several $\eta_{opt\text{-}geo,0^o}$ tests, it has been concluded an experimental value for $\eta_{opt\text{-}geo,0^o}$ of (63 ± 3)% for CAPSOL-01 (see Figure 3 left). Considering that the tests were not exactly done at ambient temperature, these results are very satisfactory. To determine the error associated to these experimental values it was considered statistical error but also instrumental uncertainties. Figure 3 right shows preliminary results of $\eta_{opt\text{-}geo,0^o}$ for CAPSOL-02. In this case mean value is (64 ± 5)%, which is slightly higher than the first prototype one, but this is not the final result because more tests with for CAPSOL-02 will be done. Peak optical-geometrical efficiency will be considerably increased in future prototypes, which will incorporate transparent covers with anti-reflective coatings.

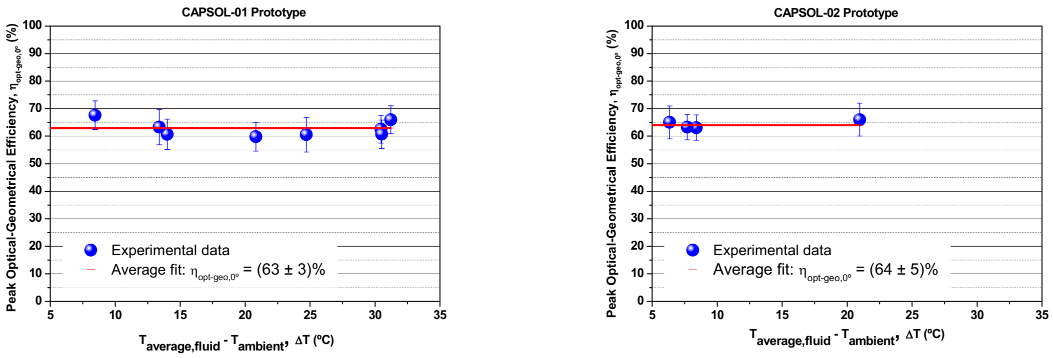

Figure 3. Experimental results of peak optical-geometrical efficiency of CAPSOL-01 (left) and CAPSOL-02 (right).

3.2 Incidence angle modifier, *K(φ)*

Figure 4 left shows the results obtained during two *K(φ)* tests with CAPSOL-01 and Figure 4 right presents the results of one incidence angle modifier with CAPSOL-02. All tests were done during the whole day to compare morning and afternoon results. Average curves are quite similar, because no changes affecting *K(φ)* has been introduced.

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

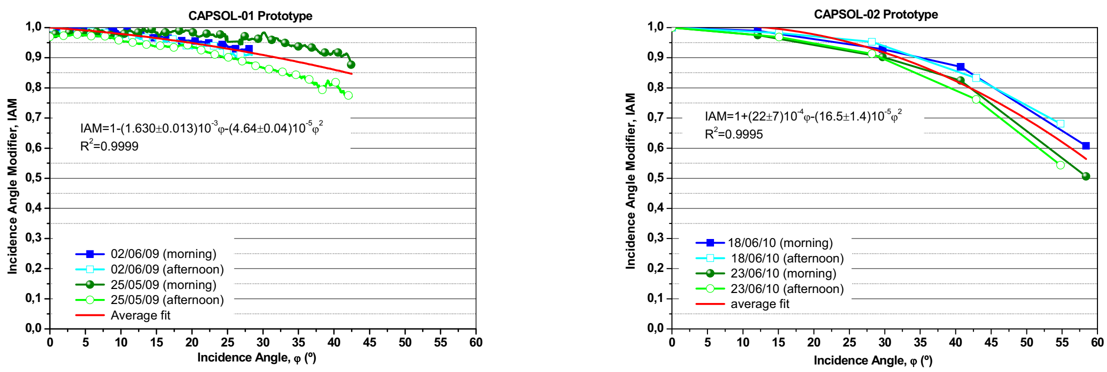

Figure 4. Experimental results of incidence angle modifier of CAPSOL-01 (left) and CAPSOL-02 (right).

3.3 Thermal efficiency, $\eta_{thermal}$

Figure 5 shows results of thermal efficiency tests campaign for CAPSOL-01. Although thermal efficiency testing with CAPSOL-02 prototype has already started, there are still not enough data to include in this paper.

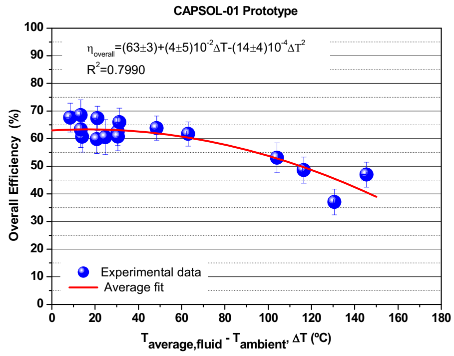

Figure 5. Experimental results of overall efficiency of CAPSOL-01.

4 Conclusions

A new small-sized PTC for applications requiring thermal energy at temperatures up to 250ºC has been developed under the CAPSOL project. The first prototype, CAPSOL-01, has been successfully designed, manufactured and tested. A second prototype, CAPSOL-02, has also been manufactured, with some improvements determined during the first-prototype assessment. Testing of CAPSOL-02 is still underway. The CAPSOL collector is expected to be commercially available by the end of 2010.

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