Optical and thermal characterization of solar receivers for parabolic trough collectors

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Abstract

Concentrating Solar Power Technology (CSP) is nowadays growing mainly due to the technical and economic success of the first projects and to the stable green pricing or support mechanisms that bridges the initial gap in electricity costs (i.e. feed-in tariffs). Future growth will depend on a successful cost reduction and on a strong effort in R&D to optimize the potential for technical improvement [1]. Testing of new materials, components and systems is still of key importance to drive research and innovation improvements to a commercial stage. Parabolic Trough Receiver (PTR) manufacturers are investing in R&D in order to improve performances and reduce costs, while project developers are demanding standards to help them to evaluate satisfactorily the risks and the benefits of introducing new developments in commercial power plants. The Solar Thermal Energy Department of the National Renewable Energy Centre (CENER) and the Photonic Technologies Group of Zaragoza University (UZ) have joined efforts to develop a characterization equipment able to measure as far as possible most of the receiver optical and thermal properties. In this paper the testing facility developed by CENER-UZ is described. The methodology for optical and thermal characterization of solar receivers for parabolic trough collectors is outlined and the first functional validation results are presented.

1. Introduction

In the latest years CSP power plants have experienced a significant growth, which has been especially noticed in Spain. Up to now, an installed power of more than 800 MW in solar thermal power has been reached around the world. Spain is one of the countries with a highest dynamism in activities of this sector with 10 solar thermal power plants (382.4 MW) already in operation and 16 solar thermal power plants (718 MW) under advanced construction. Other countries, like USA, are also playing a very important role in this market with more than 400 MW currently under operation.
As just said, thousands of solar receivers have been installed worldwide with no standardization quality control to be monitored. The core component of parabolic trough collectors, the receiver, has a strong impact on the efficiency of CSP plants. The emerging status of CSP technology demands these standardization procedures, not only during erection and assembly of the receivers, but also while operating and after several years of service life. The overall receiver efficiency is dependent on the efective aperture length, transmittance of the glass envelope, optical values of the absorber coating and vacuum quality. Today's receiver manufacturers claim for new receiver developments with better selectivity values α/ε, high transmittance, higher operating temperatures and lower thermal losses[2] [3].

The solar industry as final user of these new developments is asking for standardized characterisation and certification procedures. Recently, the Spanish Association for Standardisation and Certification (AENOR) has created the solar thermal electric subcommittee. One of the priority areas of this subcommittee will be to establish procedures for the standardisation of CSP plant components. This standardization process will allow not only a better quality control of the components, but also a starting point to ask for guarantees in case that eventually the receivers would behave out of specifications on site.

The Solar Thermal Energy Department, of the National Renewable Energy Centre (CENER) and the Applied Optics Department of the Photonic Technologies Group from Zaragoza University have joined efforts to develop a characterization equipment able to accurately measure simultaneously the spectral receiver absortance and the glass envelope transmittance; the measurement of emissivity with the required accuracy is not possible due to the optical properties of the glass envelope. Up to now, the optical test bench is the only equipment able to perform the optical characterization measurements at different receiver working temperatures, leading not only to a more complete and accurate measurement of receiver properties, but also to a more comprehensive evaluation of receiver efficiency.

At this moment the final test bench design has been completed and different functional test have been performed. A technical description of the equipments and the first experimental results are presented and discussed in the sections below.

2. Characterization of Solar receivers for Parabolic Trough Collectors

2.1. State of the art Parabolic Trough Receivers (PTR)

The parabolic trough principle lies in concentrating the sun radiation with a reflector to a linear absorber tube (receiver) transferring the solar energy gain to a heat transfer fluid (HTF), see Fig.1. The ordinary operational working temperatures of the HTF in a parabolic trough solar power plant are in the range of 290ºC to 390ºC.

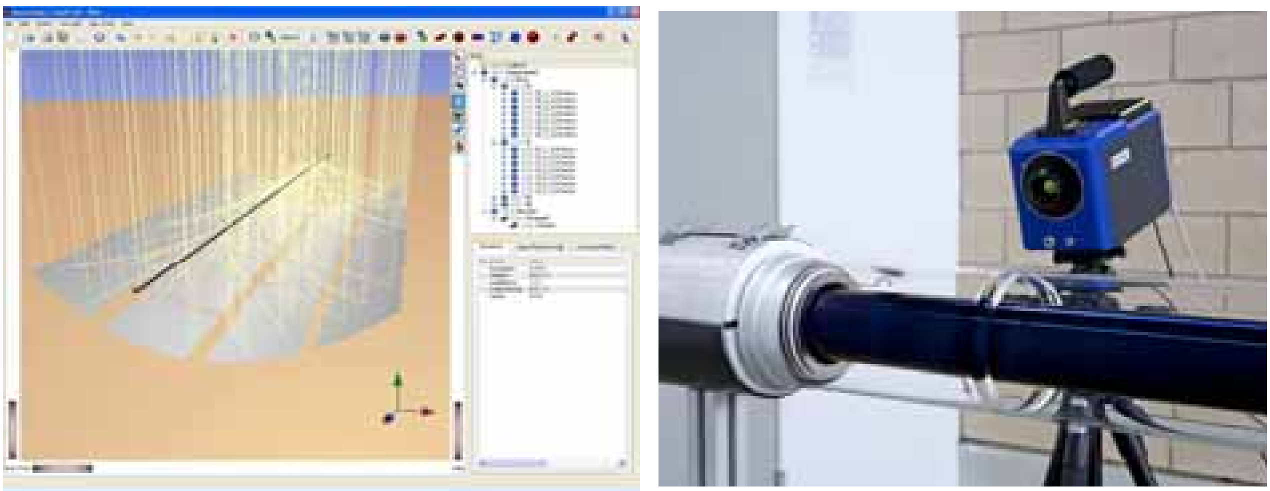

Fig. 1. Parabolic trough principle – left, Detail of a PTR – right. Source: CENER

The PTR consists of two different tubes: an internal metallic tube (where the HTF circulates) and an external glass envelope tube. The metallic tube is made of steel with a high absorptance selective coating (>95%) with low thermal emittance (<14% at 400 ºC). The glass envelope protects the absorber selective coating which degrades in contact with air, and reduces the convection thermal losses of the receiver, a vacuum insulation (pressure<10^{-3} mbar) in the annulus chamber between the metallic and the glass envelope is required.

Both ends of the glass envelope are joined with a glass-to-metal seal to the bellows welded at the end of the interior steel tube. Bellows allow the thermal expansion of the steel tube when reaching the operating condition temperatures. The glass-to-metal seal is one of the most sensible points of the PTR because it has to stand a high thermal stress. In order to reduce this thermal stress, new material combinations with adjusted thermal expansion coefficients are developed. The glass envelope has also an anti-reflective (AR) coating in both sides to ensure a high solar transmittance (>94%).

The PTR also includes another element named “getter” which maintains and indicates the vacuum level in the annulus by absorbing substances that can be generated during the PTR lifetime.
For CSP plants, a life span longer than 20 years is required and during operation PTR are mechanically and thermally stressed. The following issues which influence the thermal and optical performance of the PTR

must be assured: a fail-safe glass-to metal seal, stability of the vacuum in annulus, durability of the selective absorber coating, durability of the glass envelope AR coating.
The latest PTR generations have a thermal emittance below 10% at 400 ºC and a glass solar transmittance ≥ 96%.

2.2. State of the art of current measurements techniques

The thermal characterization testing procedures for a PTR can be performed with different test bench approaches and complexity. It can be determined:

- Outdoor: usually performed in complete solar collector assembly (SCA) test loops or collector module azimuth rotating test platforms, by measuring the heat transfer fluid (HTF) flow and temperature difference between inlet and outlet to calculate the solar energy gain

- Indoor: by using electrical heating elements to characterize the thermal losses of the PTR at the same CSP plant operating temperatures

The optical characterization can be performed with two different procedures: destructive and non destructive measurement techniques.

Destructive techniques use equipments for measuring the optical properties referred in the literature [4]. Among these measurement equipments, the following ones can be highlighted:

- Double beam reflectivity measurement equipment for UV-VIS-NIR able to measure with variable angles
- Fourier transforms far IR measurement equipment with accessories for measuring reflectance

Non destructive techniques allow measuring the optical properties of the same PTR sample in a sequential way and/or coupled with the thermal characterization or accelerated ageing tests.

Up to now, there are no specific standards covering the optical and thermal characterization procedures for PTRs, for this reason the characterization methodology under development must be validated with similar testing procedures performed by other laboratories verifying that the results obtained are in line with them.

2.3. PTR thermal characterization

The indoor test bench for thermal characterization uses two electrical heating assemblies that can be coupled inside the PTR absorber tube to heat it up to the desired operating temperatures. The goal of the test bench is to obtain the PTR thermal losses curve per unit length. This curve is very important because it is usually an input for the simulation tools used to predict the annual performance of a parabolic trough CSP plant.
An electrical power is supplied to the heating assemblies to maintain the absorber temperature. When a desired steady-state temperature is reached, the measured electrical power equals the PTR heat losses.

The key element of the test bench are the electrical heating assemblies consisting of an electrical resistance with 2 m length and Inconel spacers inserted in a 54 mm external diameter copper tube, and two end coil electrical heaters of 3 cm width. The electrical heating assembly is introduced inside the PTR by one end, and a second heating assembly is also introduced by the other end. The coil heaters are located just before and just after the end of the PTR creating an adiabatic boundary to avoid end losses. The copper tube enables the heating assembly to maintain a uniform temperature distribution inside the PTR under test. PTR thermal losses are measured without considering the wind influence.

Thermal test bench critical points:
- Heating temperature uniformity along the PT absorber tube
- Test bench PTR support which allows thermal expansion during thermal characterization tests
- Create an adiabatic wall with the coil heaters at the PTR ends
- Good contact of the temperature thermocouples in the metallic absorber inner wall

The thermal characterization methodology is based on a measurement procedure developed by NREL [3] [5]. The process starts when heating assemblies are inserted into a PTR and its electrical power is increased slowly, until the absorber temperatures approach the desired temperature value. Then the power to the coil heaters is adjusted in the way that the outer copper temperatures are equal to the inner copper temperatures creating adiabatic boundaries at the tube ends. During the process a data logger system records temperatures and powers every 5 seconds. A steady-state is reached when heater set points are fixed and the absorber temperatures logged are constant in time (variation ≤0.5ºC during a minimum period of 15 minutes). By repeating the measurement of the electrical power supplied at steady-state for different absorber temperatures, evenly spread through the PTR operating range (100ºC to 500ºC), the thermal losses curve per unit length can be obtained.

Fig. 2. PTR thermal characterization test bench with IR camera. Source: CENER

2.4. PTR optical characterization

The indoor test bench for optical characterization of PTRs involves optical spectrum characterization of reflection at any surface point of the absorber tube and optical spectrum characterization of transmission at any transverse section of the external glass envelope.

For these purposes, an optical sensor head (OSH) including both optical channels, reflexion channel (RC) and transmission channel (TC), moves along the length of the PTR whereas the PTR can be rotated. The wavelength scanning module (WSM) provides the optical signals for both reflexion and transmission optical spectra measurements in the wavelength range from 300 nm up to 2500 nm. A desired wavelength from the light source is selected and conducted to the optical paths which accommodate to the OSH. The OSH implements the optical paths for the transmission and the reflexion (TC and RC), allowing PTR transmittance and reflectance non destructive measurements.
For calibration purposes, a standard calibration composed by a high reflectance metallic inner tube and a high transmittance external glass tube is used.

The optical characterization methodology needs an intermittent calibration process of the TC and RC channels, by using the calibration standard. The calibration is required in order to get a reflectance standard for the inner metallic tube and a transmission standard for the external glass envelope. During the optical measuring process, OSH and PTR remain fixed. Transmission and reflection optical spectra curves are measured simultaneously. Wavelength scanning from 300 nm to 2500 nm can be carried out in steps of 5 nm in order to fulfil any existing optical measurement standard, in particular according to ISO 9845-1 [6], ASTM E 424 – 71 [4] or EN 410 standards.

The OSH moves along the PTR length by means of the linear translation unit. For each position of the OSH, the PTR can be rotated 360º.

2.5. Evaluation method from the PTR features to the overall CSP plant

The test bench developed by CENER-UZ allows to determine not only thermal, but also optical characteristics of the PTR. Indeed absorptance of the absorber tube and transmittance of the glass envelope can be measured with accuracy at various operation temperatures, while emissivity is not directly measured but can be deduced from thermal testing. The characteristic curve of the PTR thermal losses per length unit can be fitted to determine empirical heat transfer coefficients. These heat transfer coefficients and the measured optical properties are inputs for simulation tools, such as SimulCET [7], for predicting the annual performance of a parabolic trough CSP plant.

Heat loss coefficients could be deduced from the previous measured curves and entered in SimulCET, then annual simulations could be run to quantify how much thermal and electric power could be gained with advanced PTR features. Our first sensitivity analysis show an annual energy increase of 4% by changing a regular PTR of 14% emittance with an improved one of 9% emittance, for a 50 MW PT plant. A lot of similar studies can be performed to assess PTR modifications, such as geometry changes, selective coating improvements, vacuum conditions, etc. Besides measured heat loss curves can be compared to results from dynamic computational models like DinaCET [8] to analyze the dynamic behaviour of the tubes.

3. Measurement results for validation purposes

The results presented in this paper are preliminary, measured during the functionality validation process after the construction of the optical and thermal characterization test benches.

3.1. Thermal characterization results

The Fig. 3 shows the first validation results from the thermal characterization test bench. The absorber temperatures are measured at different length points inside the PT absorber tube (at 0.5 and 1 meter from the PTR ends) as well as the power in the main heating assembly (the 2 meter length heaters) to maintain the absorber temperatures, It can be concluded that the absorber temperature stability is good enough to fulfill the steady state condition (variation ≤0.5ºC during a minimum period of 15 minutes), but further development is needed to smooth the heating power supplied through the PID power controllers.

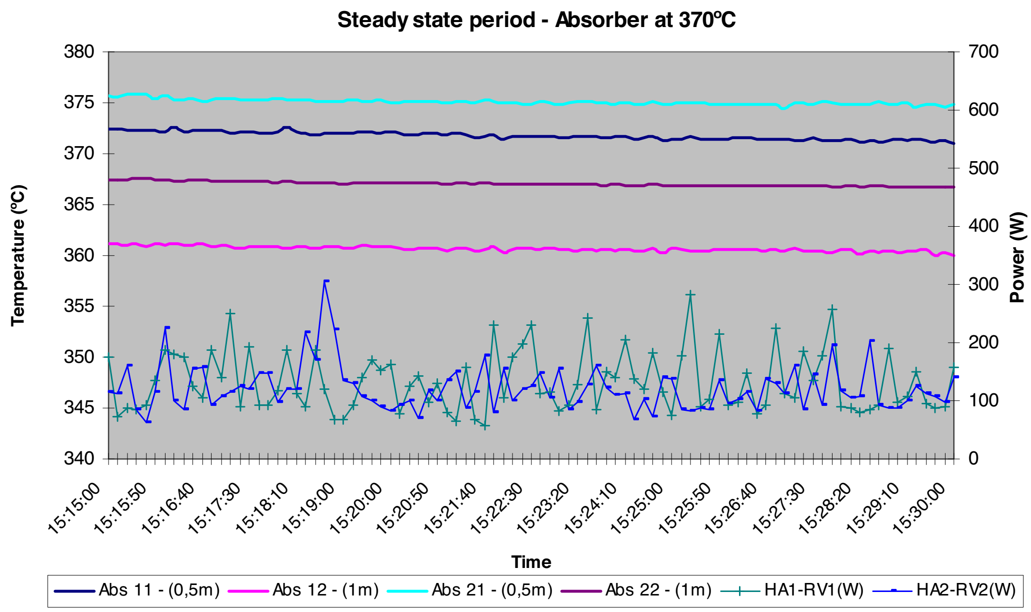

Fig. 3. Absorber temperatures and power supplied during a steady state validation test.
Source: CENER

3.2. Optical characterization results

The first optical results for transmittance and reflectance are measured on a Schott PTR70 receiver. The measurements are part of the setup and functionality validation process; see Fig. 4 and Fig. 5. In this case, the measured wavelength range is from 350 nm to 2300 nm.

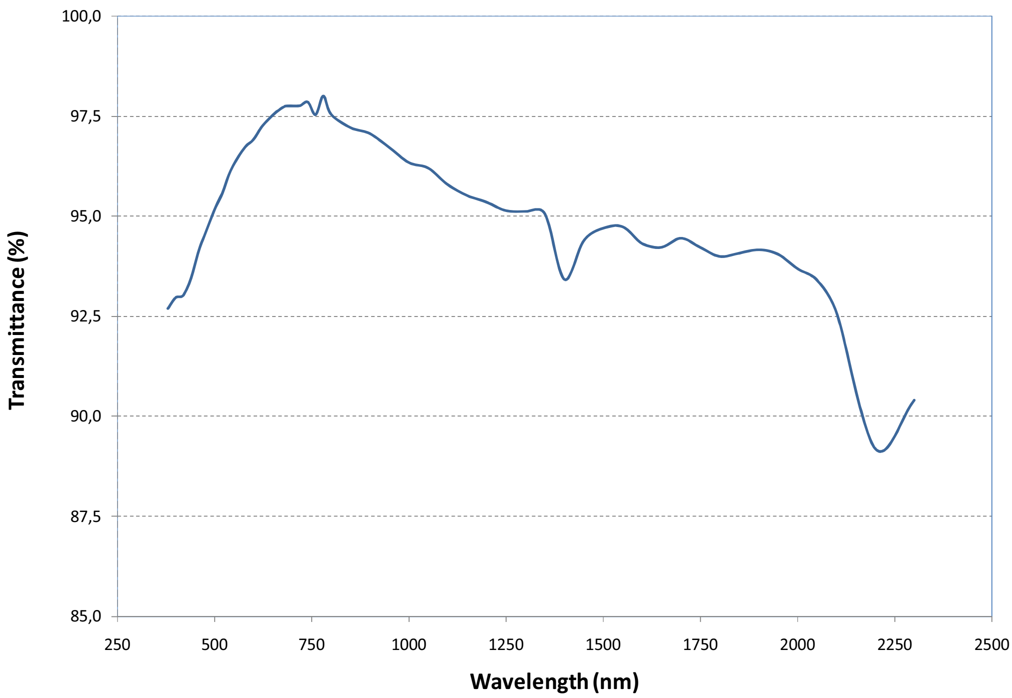

Fig. 4. Schott PTR70 AR-glass envelope transmittance results. Source: CENER – UZ

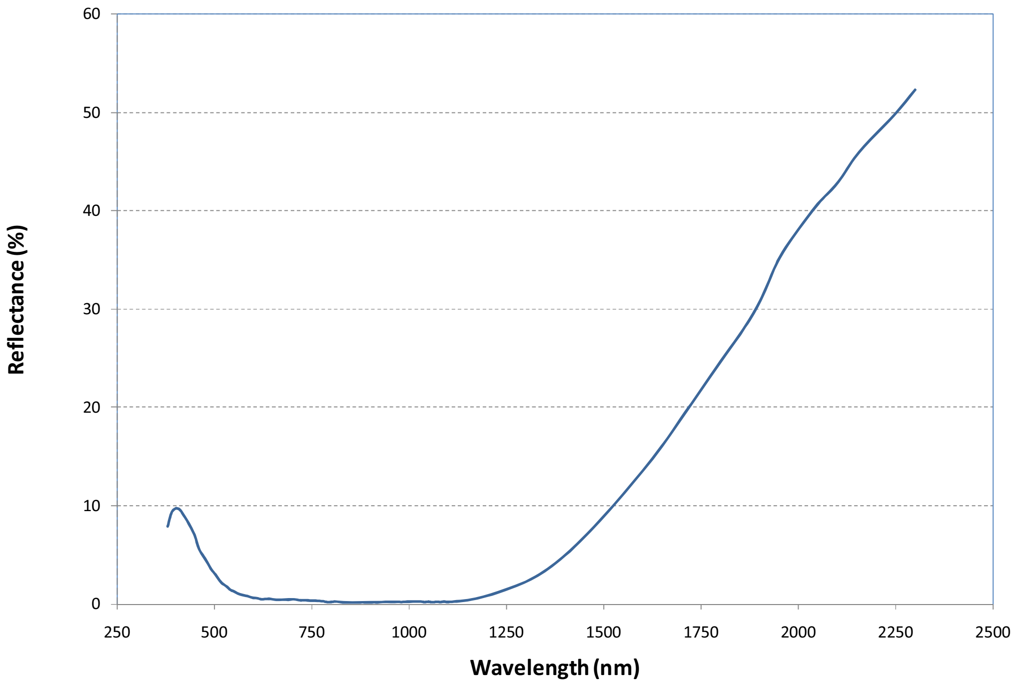

Fig. 5. Schott PTR70 absorber tube reflectance results. Source: CENER – UZ

4. Conclusions

The first optical results obtained for a Schott PTR70 receiver are in line with similar manufacturer measurements performed by other testing labs [9]. The functionality validation results are promising but a complete PTR optical and thermal characterization is needed and a study of the influence of the spectral measurement step of the optical test bench in the final results has to be performed in order to outline the optical characterization procedure for PTR.

The commercial activities start-up phase for the PTR characterization is foreseen during autumn 2010.

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