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Validation of a Parabolic Trough Solar Receiver Model based on Physical Formulation of the Absorber Total Emissivity from its Spectral Emissivity

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The present work arises from an internship agreement between the Public University of Navarre (UPNA) and the National Renewable Energy Centre (CENER). As a result of part of this internship, a paper has been written in order to be sent to the journal Solar Energy. Here a draft of that paper is presented as final degree work.

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Abstract

Concentrating solar power is an important way of providing renewable energy. Model simulation approaches play a fundamental role in the development of this technology and, for this, an accurately validation of the models is crucial. This work presents the validation of the heat loss model of the absorber tube of a parabolic trough plant by comparing the model heat loss estimates with real measurements in a specialized testing laboratory. The study focuses on the implementation in the model of a physical-meaningful and widely valid formulation of the absorber total emissivity depending on the surface's temperature. For this purpose, the spectral emissivity of several absorber's samples are measured and, with these data, the absorber total emissivity curve is obtained according to Planck function. This physical-meaningful formulation is used as input parameter in the heat loss model and a successful validation of the model is performed. Since measuring the spectral emissivity of the absorber surface may be complex and it is sample-destructive, a new methodology for the absorber's emissivity characterization is proposed. This methodology provides an estimation of the absorber total emissivity, retaining its physical meaning and widely valid formulation according to Planck function with no need for direct spectral measurements. This proposed method is also successfully validated and the results are shown in the present paper.

Keywords: Concentrating solar power; Parabolic trough; Heat collector element; Heat loss model; Dynamic simulation; Model validation; Absorber spectral emissivity; Radiative heat transfer.

1. Introduction

Solar energy systems can be used for a wide range of applications with significant benefits [1]. Among the solar energy technologies, concentrating solar power (CSP) is a promising way of providing renewable electricity. Its ability to store the heating of the sun during the day-light to reuse it during day-night, makes it the most cost-effective technology to provide dispatchable energy among the renewable technologies and competitive with the fossil fuel power plants [2]. Nowadays, parabolic trough collector is the most advanced technology in this field, concentrating the solar radiation with a parabolic mirror onto a linear receiver at its focal length.

Parabolic trough collectors have been subject of numerous different modelling approaches. Performing a thorough validation of the models is of great importance in order to guarantee accurately simulations. An exhaustive review of the parabolic trough collector modelling can be found in the work by Zaversky et al. [3].

The heat collector element (HCE) is a critical component for the performance of the solar power plant because it is where solar energy is converted to thermal energy in the form of sensible (or sometimes latent) heat of the fluid which circulates through it. In addition, it is also where main thermal losses of a CSP plant are produced.

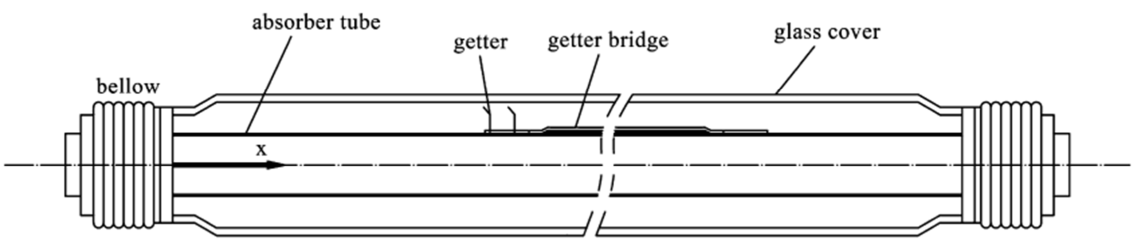

Fig. 1. Schematic of a HCE [4]

The Solar Thermal Energy Department of National Renewable Energy Centre (CENER) is currently developing and validating a complete simulation model of the performance of a solar power plant. The object-oriented modelling for the transient performance simulation of the parabolic trough collector is described by Zaversky et al. [3]. The approach of the heat loss model of the HCE is in turn based on Forristall's [4] detailed one-dimensional steady state heat transfer work. Fig.2 shows the HCE model. This model has been slightly adapted and implemented in Modelica language, and simulations have been carried out with the commercial tool Dymola and the freely available tool OpenModelica.

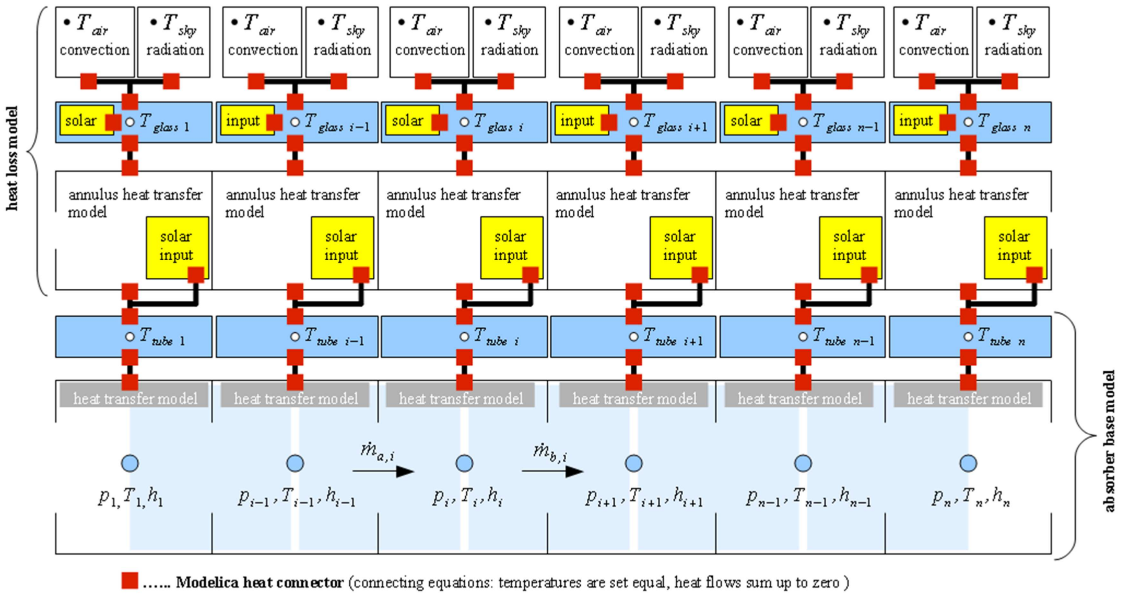

Fig. 2. HCE model scheme according to Zaversky et al. [3]

As shown in [3], validation of the complete parabolic trough collector model against data measured in a demonstration facility has been already performed showing successfully results. The objective of the present work is to perform a detailed validation with laboratory measurements of the heat loss in the HCE. However, prior to perform any validation, it is needed to provide the model with accurate input parameters to properly describe the tested component. In this sense, crucial parameters of the heat loss model are the total emissivity of the absorber tube, as well as its dependence on absorber temperature. The $\varepsilon_{abs}(T)$ is often not directly measured. Instead, it is calculated using a radiative heat transfer model: absorber temperatures (T_{abs}), glass temperatures (T_{glass}) and heat losses (HL) are experimentally measured in a laboratory test and later the $\varepsilon_{abs}(T)$ is determined by the well-known expression for two bodies radiative heat transfer:

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \quad (1)$$

This simple heat transfer model is used for experiments carried out for vacuum annulus absorber tube at high absorber temperatures, where the convective heat losses can be neglected. This methodology is described in detail by Burkholder and Kutscher [5], and the $\varepsilon_{abs}(T)$ is usually given as a function of the absorber's temperature, in the form:

$$\varepsilon_{abs}(T) = a_0 + a_2 T_{abs}^2 \quad (2)$$

CENER has been performing also this methodology in its own tests for the characterization of tubes [6].

A relationship between the emissivity and the absorber tube surface temperature based on this methodology was assumed for different validation purposes in several works [3], [7], [8].

However, expression (2) is based on a very specific empirical model that considers only the radiation. As Wirz et al. [7] had already introduced, if the expression (2) is adjusted under certain conditions in which the only-radiative model is suitable and then that $\varepsilon_{abs}(T)$ is assumed to simulate that same conditions, the agreement between the experimental data and the model results will be very good. Introducing the $\varepsilon_{abs}(T)$ obtained with this methodology would provide right results for simulation purposes as long as the operating conditions simulated were similar to the experimental testing conditions, i.e. for conditions for which the complete heat transfer model can be reasonably well described by the radiative heat transfer model exclusively. Therefore, this methodology does not guarantee the real behaviour of the $\varepsilon_{abs}(T)$ and thus, the curve (2) so adjusted is not reliable for different simulating conditions (e.g. different operating temperature range).

Furthermore, the heat loss model based on Forristall [4] approach includes an important casuistry of several aspects with physical meaning. Therefore, it is desirable that the expression of the $\varepsilon_{abs}(T)$ given in the model is due to a physical meaning too.

For all these reasons, a validation of the developed model has been performed using physical-meaningful values obtained from measured spectral emissivity data as $\varepsilon_{abs}(T)$.

2. Validation methodology

The aim is to use as input parameter in the heat loss model a curve of total emissivity unrelated to the thermal characterization lab test of the absorber tube. For this reason, samples of an absorber tube surface were sent to a laboratory. The purpose of this procedure is to achieve a validation of the developed model, using a physical-meaningful expression of the absorber total emissivity with the absorber temperature, $\varepsilon_{abs}(T)$; based on direct experimental measurements of the values of the absorber spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$.

Three absorber samples were extracted from a commercial absorber tube. The status, appearance and size of the sample were checked. No damages were observed during the cutting process. Fig.3 shows the absorber samples.

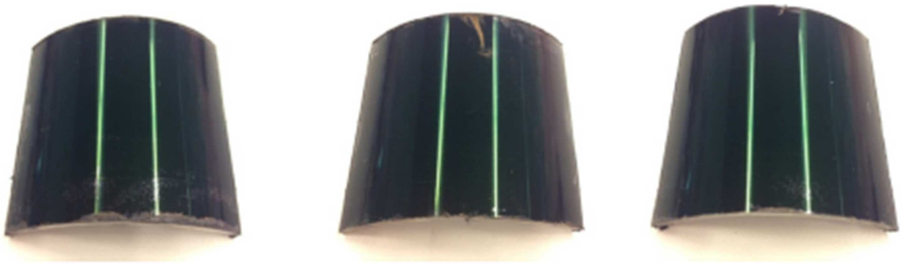

Fig.3. Absorber samples

The spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$, of the three samples was measured for short wavelengths (λ between 0.3 and 2.5 µm) and for long wavelengths (λ between 2 and 15 µm). The measurements were carried out with an UV/Vis-NIR Perkin Elmer Lambda 950 and a JASCO FT/IR 4700 LE. Fig.4 shows the spectral emissivity for short and long wavelengths of the samples average data.

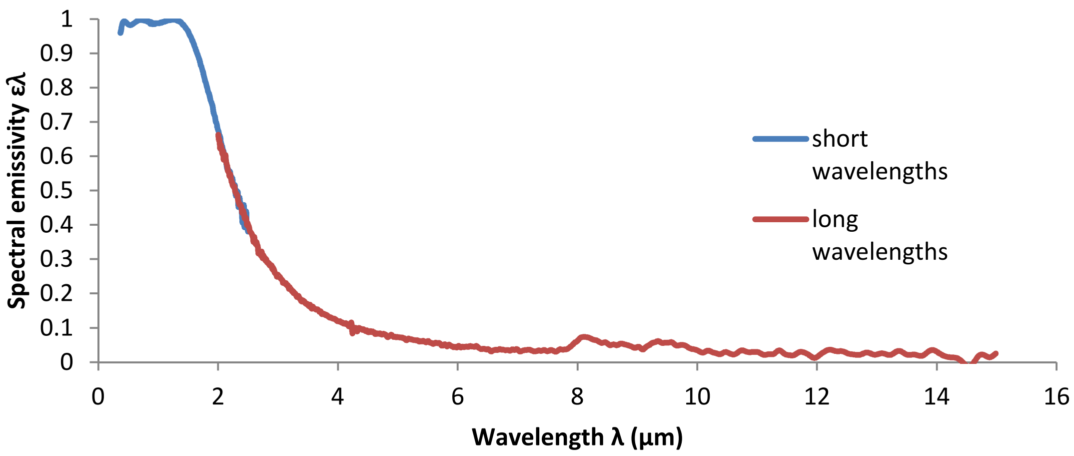

Fig. 4. Spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$, average data

The spectral emissivity values measured agree with the expected behaviour of an absorber tube surface: absorbing as much incoming solar radiation as possible and retaining the collected heat. Accordingly, it presents high absorptivity for short wavelengths (high emissivity according to Kirchhoff's law) and low emissivity for long wavelengths.

From this point on, the total absorber emissivity can be determined with physical meaning from measured spectral emissivity curve by the expression (3).

$$\varepsilon(T) = \frac{E(T)}{Eb(T)} = \frac{\int \varepsilon_\lambda(\lambda) Eb_\lambda(T,\lambda) d\lambda}{\int Eb_\lambda(T,\lambda) d\lambda} \quad (3)$$

Where $Eb_\lambda(T,\lambda)$ is the Planck function for black-body radiance at temperature T and wavelength λ.

Furthermore, according to the work of Setién-Fernández et al. [9], the spectral emissivity can be assumed constant, as expressed in equation (4), within a temperature range from ambient temperature to over 600 °C. This temperature range seems to be wide enough for any application of linear CSP and it will be considered in the rest of this work as the reference temperature range.

$$\varepsilon_\lambda(T) = \varepsilon_\lambda \quad (4)$$

In order to accurately approach the integral expression in (3), the composite Simpson rule is used (5).

$$\varepsilon(T) = \frac{\frac{h}{3}\left[\varepsilon_\lambda(\lambda_1)Eb_\lambda(T,\lambda_1) + 2\sum_{j=1}^{\frac{n}{2}-1}\varepsilon_\lambda(\lambda_{2j})Eb_\lambda(T,\lambda_{2j}) + 4\sum_{j=1}^{\frac{n}{2}}\varepsilon_\lambda(\lambda_{2j-1})Eb_\lambda(T,\lambda_{2j-1}) + \varepsilon_\lambda(\lambda_n)Eb_\lambda(T,\lambda_n)\right]}{\frac{h}{3}\left[Eb_\lambda(T,\lambda_1) + 2\sum_{j=1}^{\frac{n}{2}-1}Eb_\lambda(T,\lambda_{2j}) + 4\sum_{j=1}^{\frac{n}{2}}Eb_\lambda(T,\lambda_{2j-1}) + Eb_\lambda(T,\lambda_n)\right]} \quad (5)$$

Where: λ_1 and λ_n delimit the wavelength range, and where $h = \frac{\lambda_n - \lambda_1}{n}$.

Fig.5 shows the total absorber emissivity obtained from measured spectral emissivity values, and how is its dependence on absorber temperature. The laboratory estimates the uncertainty that can be obtained for the total absorber emissivity in ±0.01 using a coverage factor of k = 2 (95 % of confidence level). This uncertainty is also represented in Fig.5.

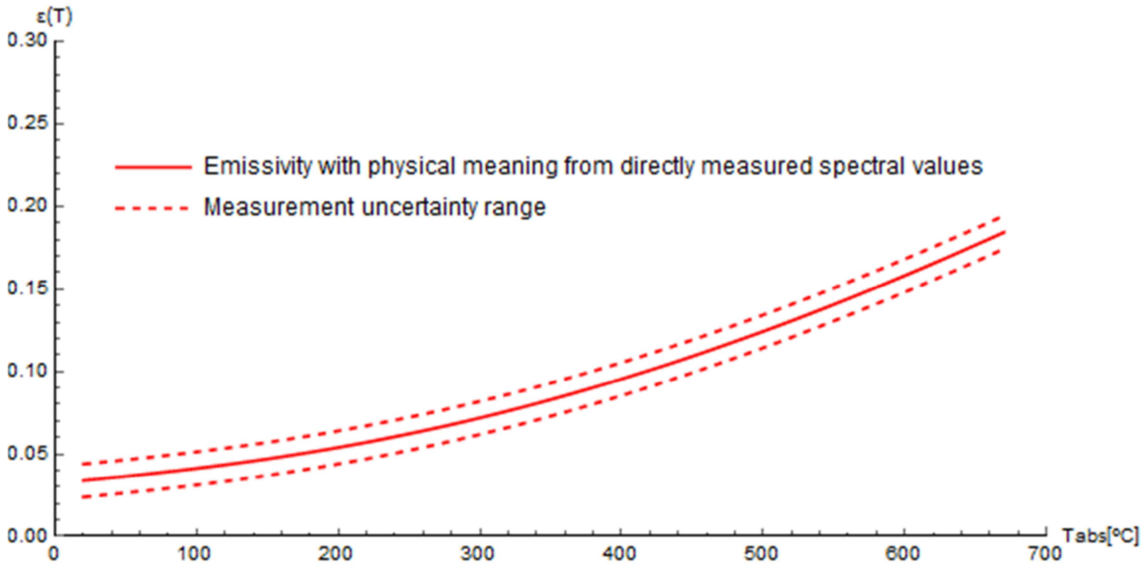

Fig. 5. Total absorber emissivity

This absorber total emissivity curve, $\varepsilon_{abs}(T)$, is therefore obtained according to its physical meaning from measured spectral emissivity values. After, it is used as input parameter in the heat loss model in order to perform the model validation.

3. Validation results

As explained before, the developed model is validated against tested experimental data. These values belong to the thermal characterization of the same commercial absorber tube for which the total emissivity has been obtained. The thermal characterization has been performed in a laboratory test according to the procedure and using the equipment explained with great detail in the works [5], [6]. The measured values of absorber temperature (T_{abs}), glass temperature (T_{glass}) and heat losses (HL) for an absorber tube with perfect vacuum in the annulus at an ambient temperature of 22 °C are showed in Table.1.

Table. 1. Experimental measures

Tabs (°C)	Tglass (°C)	HL (W/m)	u(HL) (W/m)
251.7	37.2	60.7	± 1.3
301.1	46.3	93.6	± 1.0
322.8	50.6	115.3	± 1.0
343.9	53.5	136.2	± 1.0
368.3	60.0	165.5	± 1.0
392.9	65.6	202.9	± 1.0

The result of the simulation of the glass temperatures and the heat losses are compared to the experimental data in the graphics Fig.6 and Fig.7, the uncertainties are also represented.

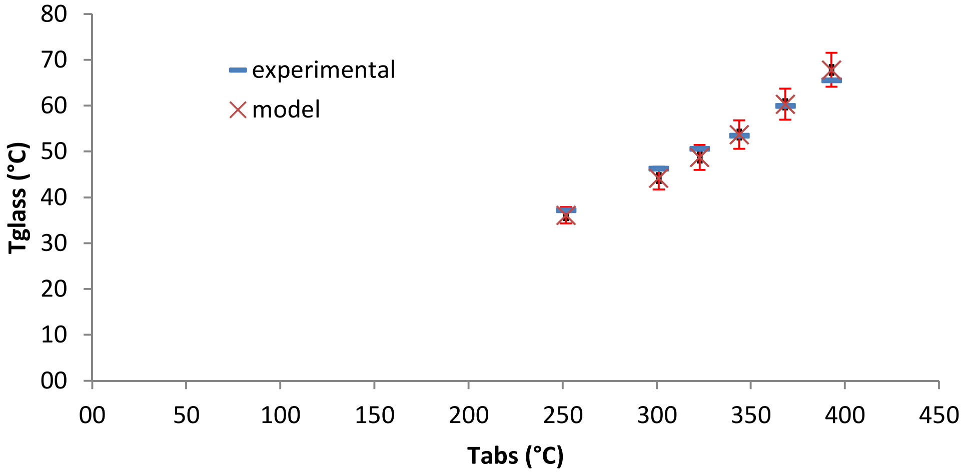

Fig. 6. Glass temperature simulated values compared against experimental data

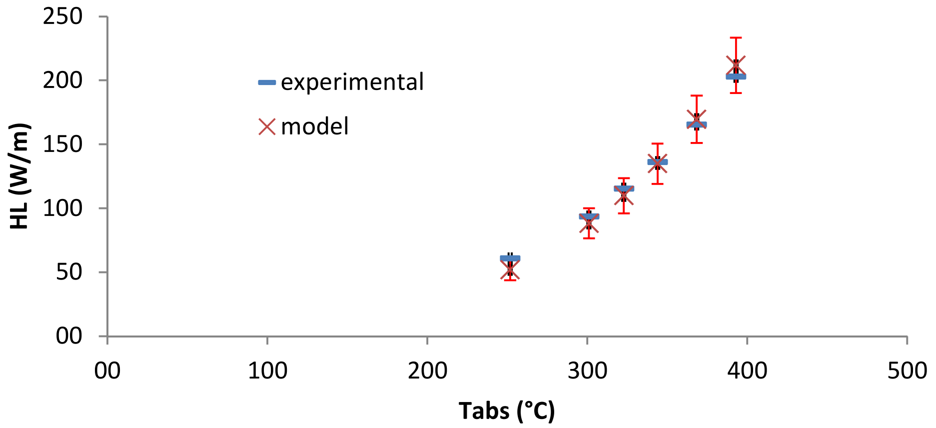

Fig. 7. Heat losses simulated values compared against experimental data

The agreement between the model and the experimental data is correct for all absorber temperatures. The model is thus validated, using as emissivity input parameter the $\varepsilon_{abs}(T)$ obtained according to Planck function from the measured values of spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$.

Fig.8 illustrates that, for the specific conditions simulated, an adjustment of $\varepsilon_{abs}(T)$ based on an only-radiative model (2) would provide reasonable values at that range. However, Fig.8 shows also that, as aforementioned and expressed by the works [5], [6], [7], that curve is only reliable in a specific temperature range; while implementing in the model $\varepsilon_{abs}(T)$ according to the Planck function approach guarantees its reliability for any other conditions (e.g. wider temperature ranges), because it has always a physical correlation behind.

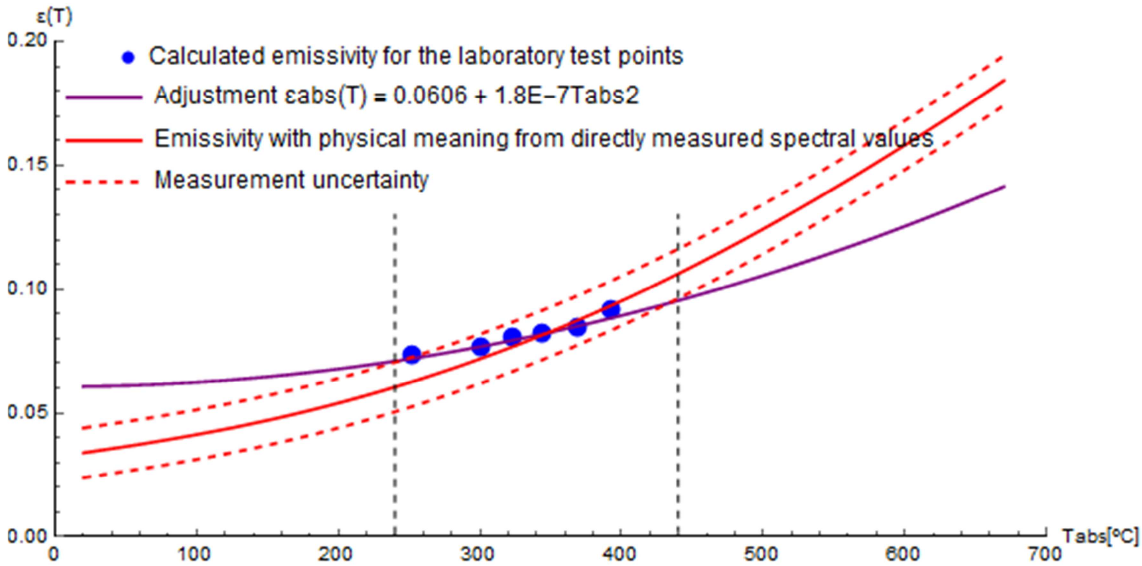

Fig. 8. Absorber total emissivity comparison between radiative-empirical approach and spectral physical-meaningful approach

On the other hand, the radiative-empirical approach is a non-destructive methodology. If it is desired to use in a model a spectral physical-meaningful approach of the absorber total emissivity, it is not practical to cut every time a tube in order to extract some samples to measure its spectral emissivity. Therefore, in this work a new methodology for absorber total emissivity characterization is proposed, valid for giving a curve of ε_{abs}(T) from laboratory tests as well as for using a physical-meaningful ε_{abs}(T) in models for simulation.

4. Proposed methodology for absorber emissivity characterization

In order to obtain experimental data from the type of receiver tube that is wanted to characterize, a thermal characterization of a vacuum annulus tube is performed in a laboratory test according to procedure described in works [5], [6]. It is assumed that at high absorber temperatures (e.g. within a temperature range between 300 and 400 °C), procedure [5] provides reliable and useful calculated values of absorber total emissivity, because at these conditions the heat loss behaviour can be well described by the radiative heat transfer model (1).

In addition, the appearance of the spectral emissivity of a receiver tube along the wavelengths is well known: high emissivity for short wavelengths and a fast decrease to low emissivity for long wavelengths. This behaviour can be approximated by a maximum value (ε_{max}) at short wavelengths and by a potential expression from some value of wavelength (λ_0) to long wavelengths:

$$\varepsilon_{abs,\lambda}(\lambda) = \begin{cases} a\lambda^b, & if\ \lambda \geq \lambda_0 \\ \varepsilon_{max}, & if\ \lambda < \lambda_0 \end{cases} \quad (6)$$

This approach is proposed through the experience of the common appearance of the spectral emissivity behaviour in the absorber tubes. Fig.9 and Fig.10 show an example illustrating the agreement between the proposed approach appearance and the appearance of real $\varepsilon_{abs,\lambda}(\lambda)$ in different absorber coatings and different conditions. The three first curves showed in Fig.10 were obtained by direct experimental measurements of ε_λ, and the fourth curve was published by Setién-Fernández et al. [9].

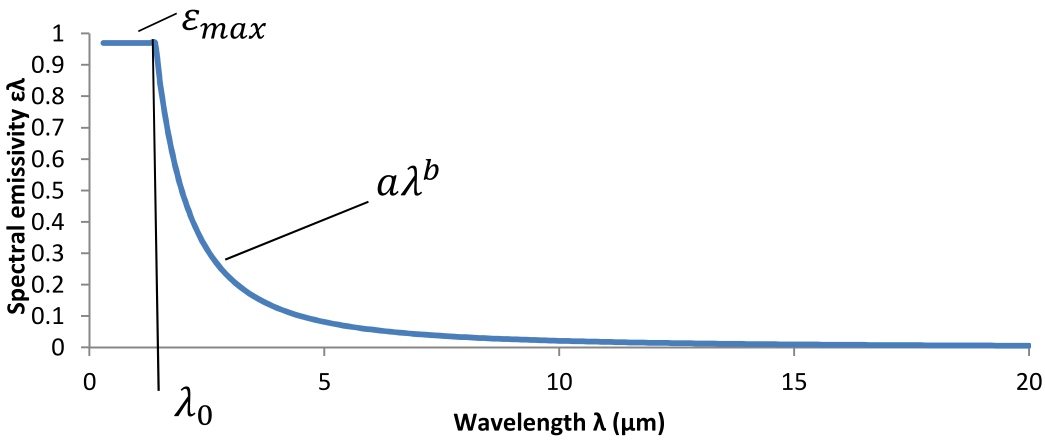

Fig. 9. Proposed spectral emissivity approach

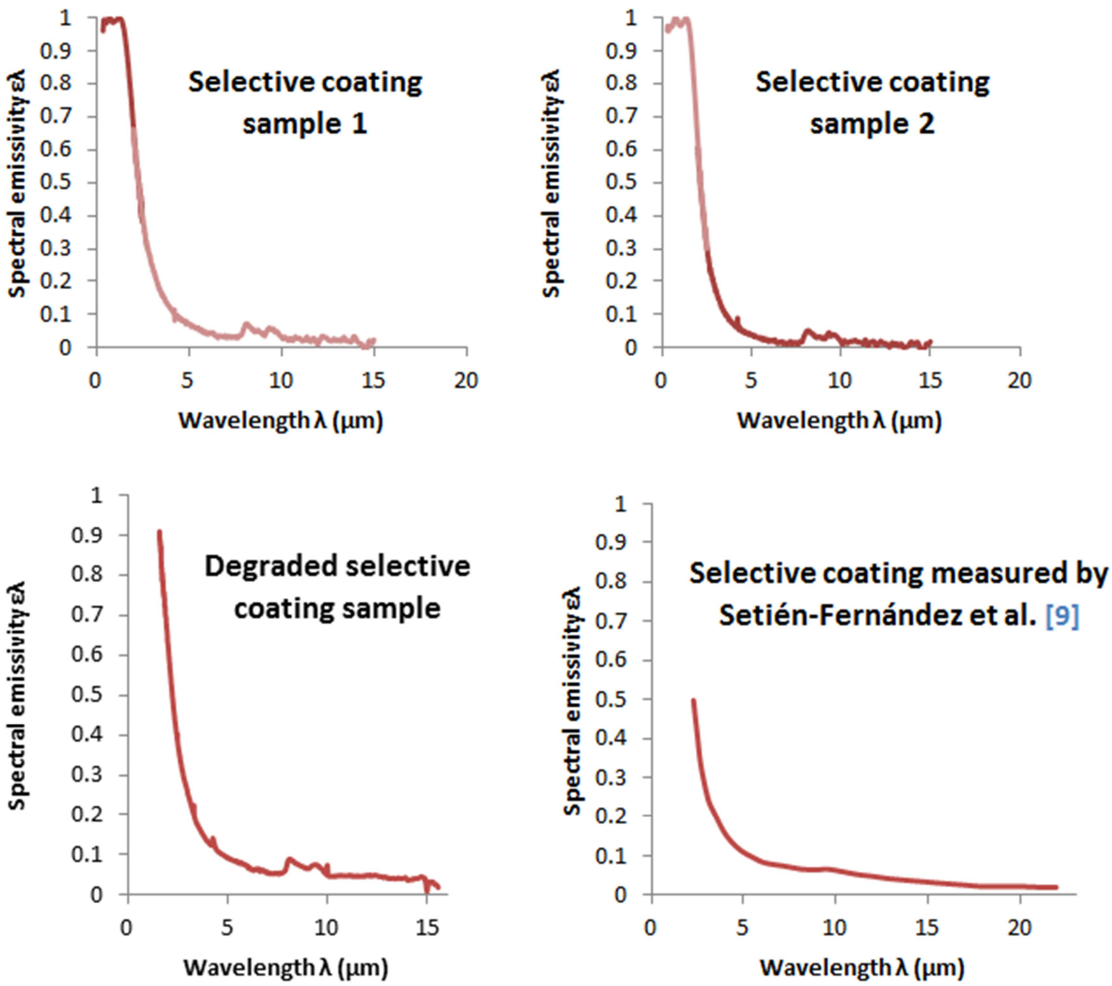

Fig. 10. Experimental measurement of the spectral emissivity of various samples of parabolic trough absorber selective coatings

Therefore, the parameters a and b can be adjusted in such a way that:

- The approximation of $\varepsilon_{abs,\lambda}(\lambda)$ represents a realistic spectral behaviour.
- $\varepsilon_{abs,\lambda}(\lambda)$ is due to a physical-meaningful approach according to Planck function

- It fits the experimental calculated values of absorber total emissivity $\varepsilon_{abs}(T)$ at high temperatures according to procedure [5].

The adjustment is performed by the following least squares adjustment minimizing:

$$\varepsilon(T_1) = \frac{\int_{\lambda_1}^{\lambda_n} \varepsilon_\lambda(\lambda) Eb_\lambda(T_1,\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_n} Eb_\lambda(T_1,\lambda) d\lambda}$$
$$[\ldots] \qquad (7)$$
$$\varepsilon(T_k) = \frac{\int_{\lambda_1}^{\lambda_n} \varepsilon_\lambda(\lambda) Eb_\lambda(T_k,\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_n} Eb_\lambda(T_k,\lambda) d\lambda}$$

Where $\varepsilon(T_1)$, […], $\varepsilon(T_k)$ are the particular values of absorber total emissivity calculated according to the procedure by Burkholder and Kutscher [5]. In addition, the continuity condition ($a\lambda_0^b = \varepsilon_{max}$) is imposed for this adjustment. Reasonable values for the parameters ε_{max} and λ_0 are 0.97 and 1.5 µm respectively. These values have been suggested based on the experience as observed in several commercial CSP receiver tubes. They are however the selective coating main design parameters and they can be obtained or estimated through different criteria (e.g. manufacturer data, material properties, related literature).

Once the parameters a and b have been adjusted, the result is the curve of the evolution of the spectral emissivity over the wavelength spectra. This is the same notion as the curve showed in Fig.4, which was obtained before by measuring some receiver's samples in a laboratory.

From this point on, the procedure is the same as in the section 2: from a realistic curve of the absorber spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$, the behaviour of the absorber total emissivity with the temperature, $\varepsilon_{abs}(T)$, according to Planck function is obtained. The result is a physical-meaningful $\varepsilon_{abs}(T)$ curve that can be used in the models for simulation purposes.

5. Results of the proposed methodology

The heat loss model is validated again, using in this occasion as emissivity input parameter in the model, the absorber emissivity, $\varepsilon_{abs}(T)$, obtained with the new proposed methodology. For this validation, the tube and the simulating conditions are the same as in the third section, and the experimental data are also the ones previously described and shown in Table.1.

The validation is performed as if there were no absorber spectral emissivity measurements ε_λ (quite the opposite than in the validation shown in the section 3). In this case, $\varepsilon_{abs}(T)$ is obtained by applying the methodology proposed in section 4 for the absorber total emissivity characterization.

The particular values of the absorber total emissivity, $\varepsilon_{abs}(T)$, required to adjust the spectral emissivity curve are calculated according to procedure [5] from the experimental data showed in Table.1 and related to absorber temperatures higher than 300 °C. With these data, the aforementioned adjustment of parameters a and b is performed, obtaining the following approximation of the spectral emissivity:

$$\varepsilon_{abs,\lambda}(\lambda) = \begin{cases} 2.15596\lambda^{-1.96983}, & if\ \lambda \geq 1.5\ \mu m \\ 0.97, & if\ \lambda < 1.5\ \mu m \end{cases} \qquad (8)$$

The agreement between this $\varepsilon_{abs,\lambda}(\lambda)$ characterization (green) and the real measured $\varepsilon_{abs,\lambda}(\lambda)$ curve (blue and red) showed in the section 2 (Fig.4) can be seen in the Fig.11.

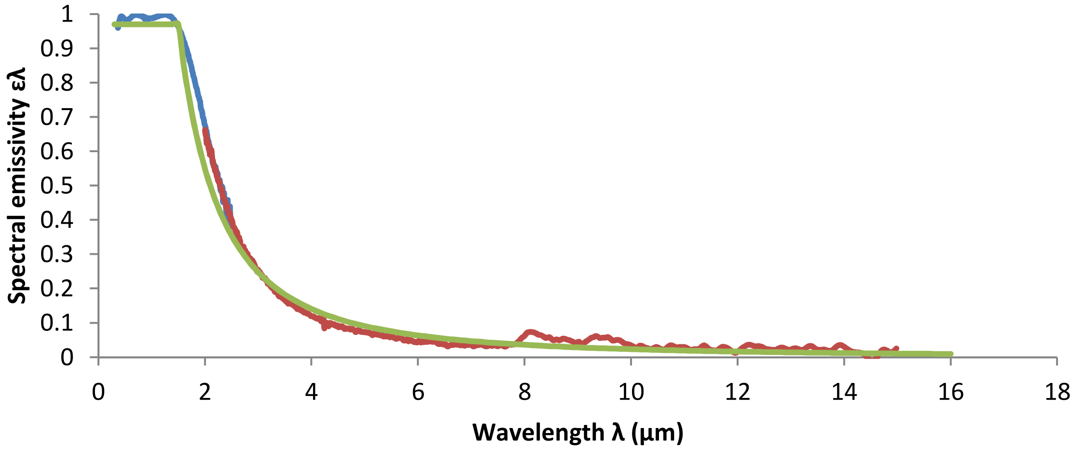

Fig. 11. Comparison between real ε_λ curve and the expression proposed

From this realistic curve for the absorber spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$, the behaviour of the absorber total emissivity with the temperature, $\varepsilon_{abs}(T)$, according to Planck function is obtained. Fig.12 shows the $\varepsilon_{abs}(T)$ obtained with this new methodology (green) and the particular values used to adjust this curve (blue points). Fig.12 also compares this obtained curve (green) with the sample-destructive measured curve used in the second section (red). Again, the agreement between this proposed non-destructive curve and the curve based on direct real measurements can be observed, in this case applied to the absorber total emissivity, $\varepsilon_{abs}(T)$.

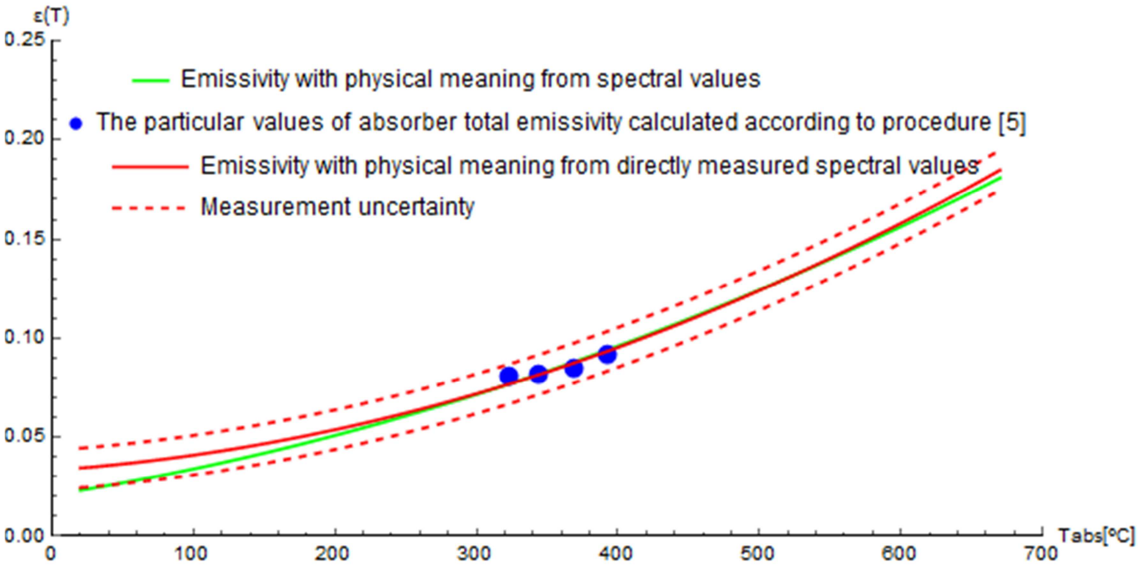

Fig. 12. Total absorber emissivity

This curve of $\varepsilon_{abs}(T)$ is the one that is used as input parameter for the emissivity in the model in order to perform the validation. This curve satisfies the same physical meaning than the curve implemented in the second section, with the difference that no spectral measurements have been needed for its calculation. The way in which the curve is implemented in the model could be complex in some cases if it is needed to implement in the model the procedure according to Planck function and the spectral emissivity curve, $\varepsilon_{abs,\lambda}(\lambda)$. Therefore, once the curve $\varepsilon_{abs}(T)$ is obtained according to Planck function, it can be reasonable to give a polynomial adjustment (9) that describes almost perfectly the curve and that is an easier way to be implemented it in the simulation model.

$$\varepsilon_{abs}(T) = a_0 + a_1 T_{abs} + a_2 T_{abs}^2 \quad (9)$$

For this particular case, the adjusted parameters result in: $a_0 = 0.0209463$, $a_1 = 0.000112844$, $a_2 = 1.88075E - 7$. It should be noticed that this expression responds only to a simpler way of providing the physical curve according to Planck function, and it is based on a completely different approach than the empirical curve described in (2).

The heat loss model validation is now performed using this estimated emissivity curve as input parameter in the model. The result of the simulation of the glass temperatures and the heat losses obtained in this new simulation are compared to the experimental data in the graphics Fig.13 and Fig.14.

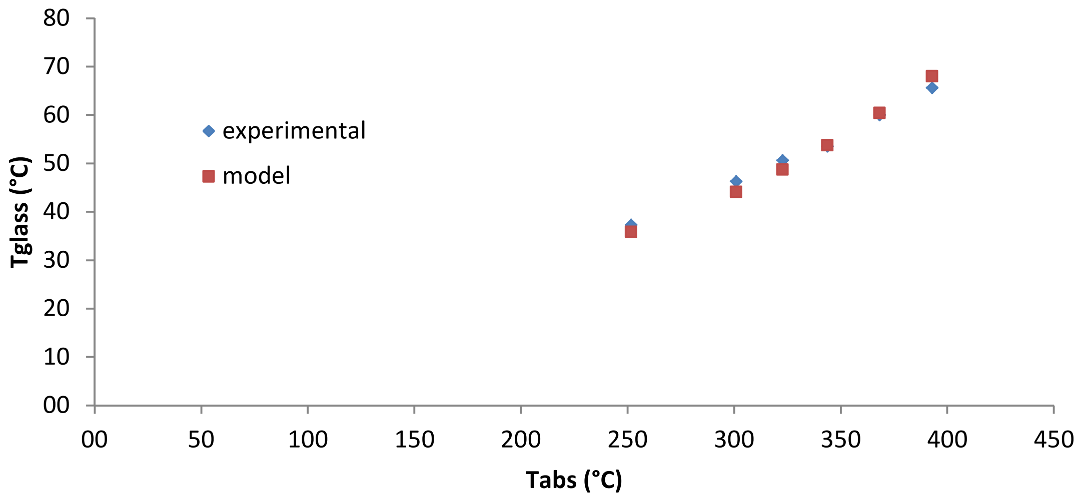

Fig. 13. Glass temperature simulated values compared against experimental data

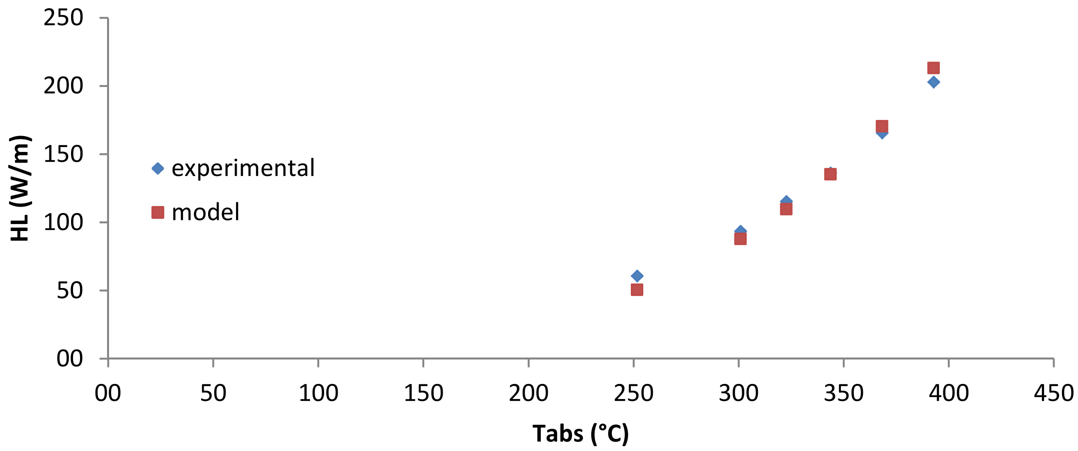

Fig. 14. Heat losses simulated values compared against experimental data

As shown in figures Fig.13 and Fig.14, the agreement between the model and the experimental data is correct for all absorber temperatures. Thus, the model is validated, using as its absorber emissivity input parameter the $\varepsilon_{abs}(T)$ according to Planck function from a calculated curve of spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$ obtained with the new developed methodology. Furthermore, it can be noticed that the simulation results obtained with this new $\varepsilon_{abs,\lambda}(\lambda)$ characterization methodology (Fig.13, Fig.14) are almost the same as the simulation results obtained with real measurements of $\varepsilon_{abs,\lambda}(\lambda)$ (Fig.6, Fig.7). This is the expected result due to the high similarity of the estimated and measured emissivity curves, as it was previously described in the figures Fig.11 and Fig.12.

6. Conclusions and further work

A successfully validation of the heat loss developed model for a parabolic trough absorber tube with perfect vacuum in the annulus by comparing the model heat loss estimates with real measurements in a specialized testing laboratory has been achieved. In this validation, a curve of $\varepsilon_{abs}(T)$ according to Planck function obtained from spectral emissivity direct measurements $\varepsilon_{abs,\lambda}(\lambda)$ has been used as input parameter for the emissivity in the model, instead of previous approaches that used empirical approaches of $\varepsilon_{abs}(T)$ based on the same laboratory results.

In addition, since measuring the spectral emissivity, $\varepsilon_{abs,\lambda}(\lambda)$, may be complex and it is sample-destructive, a new $\varepsilon_{abs}(T)$ characterization methodology has been proposed. This methodology provides a $\varepsilon_{abs}(T)$ curve that is physical-meaningful according to Planck function. This curve is obtained by adjusting a $\varepsilon_{abs,\lambda}(\lambda)$ curve that describes correctly the real spectral emissivity of the absorber, and that it matches the empirical heat losses tested at high absorber temperatures.

Identified future work includes the complete detailed validation of the complex and physical-meaningful heat loss model based on [3] for all the different operating conditions that may occur in real CSP plants (e.g. different vacuum properties in the annulus, degrades selective coating, broken glass cover, different ambient conditions in terms of temperature and wind speed). This means that the present work is the first part in a more complex work that will cover the complete physical casuistry. From now on, the developed methodology for $\varepsilon_{abs}(T)$ characterization can be used for any of these validation purposes. In this regard, an optimization of this methodology will be also subject of further work.

Nomenclature

Symbols

a	spectral emissivity coefficient (μm^{-1})
a_0	total emissivity coefficient (-)
a_1	total emissivity coefficient ($°C^{-1}$)
a_2	total emissivity coefficient ($°C^{-2}$)
A_1	heat transfer area of body 1 (m^2)
A_2	heat transfer area of body 2 (m^2)
b	spectral emissivity coefficient (-)
$E(T)$	radiance (W/m^2)
$Eb(T)$	black body radiance (W/m^2)
$Eb_\lambda(T,\lambda)$	black body spectral radiance Planck function ($W/m^2\lambda m$)
F_{12}	view factor from body 1 to body 2 (-)
HL	heat losses (W/m)
$\dot{Q}$	heat transfer (W)
T_1	body 1 temperature (K)
T_2	body 2 temperature (K)

T_{abs} absorber temperature (°C)

T_{glass} glass temperature (°C)

u(HL) heat losses uncertainty (W/m)

Greek Symbols

ε_1 total emissivity of body 1 (-)

ε_2 total emissivity of body 2 (-)

$\varepsilon(T)$ total emissivity as a function of temperature (-)

$\varepsilon_{abs}(T)$ total absorber emissivity as a function of temperature (-)

ε_{max} maximum spectral emissivity (-)

ε_λ spectral emissivity (-)

$\varepsilon_\lambda(T)$ spectral emissivity as a function of temperature (-)

$\varepsilon_{abs,\lambda}(\lambda)$ spectral absorber emissivity as a function of wavelength (-)

λ wavelength (µm)

λ_0 drop wavelength (µm)

σ Stefan-Boltzman constant (=5.67E-8 W/m^2K^4)

Abbreviations

CSP Concentrating Solar Power

HCE Heat Collector Element

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