A Novel Portable Device to Measure the Temperature of Both the Inner and the Outer Tubes of a Parabolic Receiver in the Field

J.L Navarro Hermoso[1, a)], Guillermo Espinosa-Rueda[1] , Noelia Martinez[2] , Carlos Heras[3] and Marta Osta[3]

[1]*Abengoa Research, Soland, Sanlúcar la Mayor, 41800, Sevilla, Spain*
[2] *Abengoa Research, Paseo de la Castellana, Madrid, Spain*
[3]*Universidad de Zaragoza, Grupo de Ciencias Fotónicas, Zaragoza, Spain*

[a)] joseluis.navarro@abengoa.com

Abstract. The performance of parabolic trough (PT) receiver tubes (RT) has a direct impact on Solar Thermal Energy (STE) plant production. As a result, one major need of operation and maintenance (O&M) in STE plants is to monitor the state of the receiver tube as a key element in the solar field. However the lack of specific devices so far has limited the proper evaluation of operating receiver tube´s thermal performance. As a consequence non-accurate approximations have been accepted until now using infrared thermal images of the glass outer tube. In order to fulfill this need, Abengoa has developed a unique portable device for evaluating the thermal performance and vacuum state of parabolic trough receiver tubes placed in the field. The novel device described in this paper, simultaneously provides the temperature of both the inner steel tube and the outer glass tube enabling a check on manufacturers specifications. The on-field evaluation of any receiver tube at any operating temperature has become possible thanks to this new measuring device.

The features and usability of this new measurement system as a workable portable device in operating solar fields provide a very useful tool for all companies in the sector contributing to technology progress. The originality of the device, patent pending P201431969, is not limited to the CSP sector, also having scientific significance in the general measuring instruments field. This paper presents the work carried out to develop and validate the device, also detailing its functioning properties and including the excellent results obtained in the laboratory to determine its accuracy and standard deviation. This information was validated with data collected by O&M teams using this instrument in a commercial CSP plant. The relevance of the device has been evidenced by evaluating a wide sample of RT and the results are discussed in this paper. Finally, all the on field collected data is used to demonstrate the high impact that using this unique portable device will have on a parabolic trough solar power plant.

INTRODUCTION

In a parabolic trough STE plant, the solar field has two main components, mirror troughs and receivers tubes, which must be operated at the highest possible efficiency [1] to enhance plant performance. To do so, operating plants need to characterize the properties of the installed components. Simple, accurate, portable devices are required. Mirror reflectance monitoring is performed daily in the solar field using specialized portable reflectometers [2]. Also the receiver tubes optical performance, the transmittance of the outer glass tube and absorbance of the inner metal tube, is monitored using specialized portable spectrophotometers [3] [4].

However, there are not any specific portable measuring instruments to evaluate the thermal properties of receivers in the field. All the models [5] [6] [7] which allow prediction of power plant performance and carrying out sensitivity analysis [8] consider the receiver´s thermal performance a key parameter with a direct impact on facility performance. Tube thermal performance depends on the maintenance of the vacuum between both tubes [5] [6], that reduces convective and conductive losses and assures the maintenance of the inner tube coatings [9]. Thermal

SolarPACES 2015
AIP Conf. Proc. 1734, 130015-1–130015-8; doi: 10.1063/1.4949225
Published by AIP Publishing. 978-0-7354-1386-3/$30.00

models [5][10] allow obtaining a theoretical glass tube temperature depending on the inner tube and the ambient temperatures for a specific vacuum quality state, that is gas composition and pressure. So to prove that the vacuum has lost its proper state, it is necessary to simultaneously measure the temperature of the glass envelope, the inner tube and the ambient temperature, all under normal operating conditions.

Several instruments have been developed to evaluate tube's thermal performance by calculating the outer glass tube temperature using common infrared images from a thermal camera [11] [12]. None of the techniques in the state of the art fulfills the requirements of simultaneously measuring the temperature of two concentric tubes.

Abengoa in collaboration with Universidad de Zaragoza has developed a specialized portable device to simultaneously and accurately measure the temperature of the inner and outer tubes of parabolic trough receivers.

SCIENTIFIC MEASUREMENT PRINCIPLE

Every object emits energy as electromagnetic radiation. Emissive spectral power determines the amount of energy emitted per unit surface and time between the wavelengths λ and λ+dλ. It is given by Planck's Law:

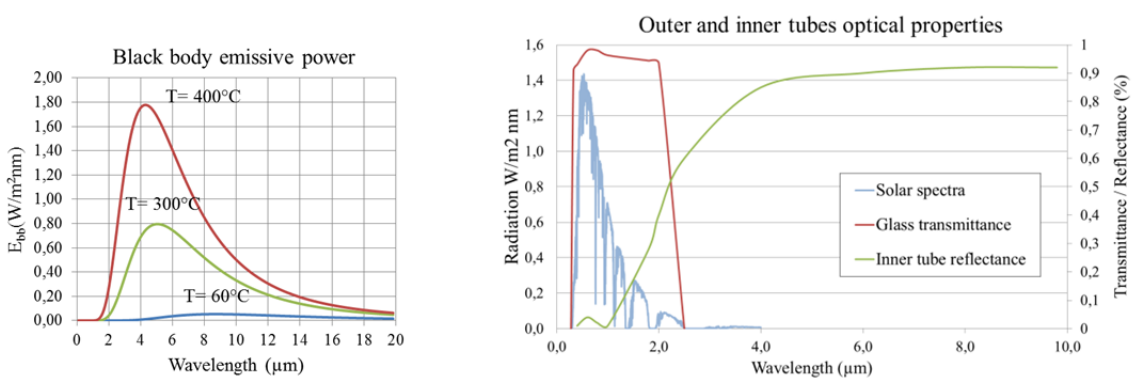
$$E_\lambda(\lambda,T)\Big|_{\lambda\to\lambda+d\lambda} = \varepsilon(\lambda)\frac{c_1}{\lambda^5\left(e^{c_2/\lambda T}-1\right)}, \quad 0<\varepsilon(\lambda)<1 \tag{1}$$

Where T is the object temperature, ε(λ) is the spectral emissivity of the surface and c1 and c2 are radiation constants

$$c_1 = 2\pi h c_0^2; \qquad c_2 = \frac{hc_0}{k}, \tag{2}$$

Where c0 = 3•108(m/s) is the speed of light, k = 1.38 10-23(J/K) is the Boltzmann constant and h = 6.63•10-34 (J•s) is the Planck constant.

During operation the receiver's temperature takes values between 300 and 400ºC for the inner tube and around 60ºC for the outer tube thanks to the vacuum insulation. Emissive spectral power emitted by a black body at these temperatures is shown in Figure 1(a). According to the Wien Law, the higher the temperature of the black body, the larger the amount of emitted energy and the lower the wavelength where the maximum is located.



(a) (b)

FIGURE 1. Power emitted by black bodies (a) and tubes optical properties (b)

The optical properties of the receiver tubes, Fig.1 (b), enhance the solar energy absorption by the inner tube and consequently the energy transmitted to the Heat Transfer Fluid (HTF) running through it. The inner metal tube coating has low reflectance in the solar spectrum [13] region (0.4-2 µm), which implies high absorbance, meanwhile in the medium and high infrared it is highly reflective and lowly absorptive, minimizing radiation losses. The outer glass tube has high transmittance in the visible and near infrared spectrum (0.4-3.5 µm), coinciding with the solar spectrum. However for wavelengths higher than 4 µm the glass tube transmittance is null, meaning that the glass is opaque and radiation does not pass through it. The glass is considered as a black body for wavelengths beyond 4 µm. The emissivity of an opaque black body (T (λ) =0) is given by (3).

$$\varepsilon(\lambda) = 1 - R(\lambda) \approx 1 \quad (3)$$

Where R (λ) is the glass reflectance coefficient in the infrared, being nearly zero (0.03-0.04) beyond 4μm.

DEVICE DESCRIPTION

The device is based on the independent and simultaneous measurement of the electromagnetic power emitted by the inner and the outer tube. An accurate measurement without contact or interferences is possible thanks to the combination of: the difference between the temperature and the emitted power spectrum of both tubes; the variable transmittance of the glass tube depending on the wavelengths; and the selection on the proper measurement spectral range for each tube.

According to Plank's law, below 3.5 μm the emission of a black body at the temperature of the glass envelope during operation is practically null compared with the emission of the inner tube at its operating temperature. This fact is used to detect and measure a defined part of the whole radiation emitted by the inner tube. Calibrating this signal coming practically exclusively from the inner tube it is possible to determine its temperature with no interference from the outer tube, which in addition is highly transparent in these wavelengths.

On the other hand, the glass opacity at longer wavelengths is used to measure the radiation exclusively coming from the outer tube and determine its temperature with no interference from the inner tube.

The device is formed by two units, the measuring unit and the control unit. The measuring unit, contains the detectors and its function is to obtain a precise electromagnetic power signal from the evaluated tubes. The measuring unit is contained in a case adapted to the tube geometry, which keeps constant the parameters which influence the measurement to assure repeatability. The system configuration avoids any influence from adjacent bodies or other radiation. The measuring unit respects the glass surface and the antireflective layer by using a minimum contact system with tiny rubber feet.

FIGURE 2. Control unit (a) and device measuring with a pole (b).

The control unit is the interface between the measuring unit and the user. Signals detected with the measuring unit are sent to the control unit wirelessly. The control unit does the data processing and conversion and is used for device control. Two control unit formats are offered to the users. The first option is a custom control unit, Fig.2 (a) that consists of an ergonomic case with backlighted digital screen and alphanumerical keyboard and equipped with an easy-to-use interface. It has high battery life, internal memory storage exportable to a computer and an ambient temperature sensor. The second option is to use a mobile or tablet, installing an available custom application. The mobile and the measuring unit are synchronized and data management and device control are performed from the mobile, exporting data to a PC or even to another application using internet connection.

Measuring and control units can be integrated in a unique system, Fig.2 (b). A pole with two connections enables rapid attachment of both modules. The measuring unit is fixed in a rotating joint and the control unit in fixed within reach of the user. This configuration facilitates an easy and rapid evaluation of multiples tubes, just placing the device on the desired tube, temperature values are shown in real time in the screen.

The device measurement range is from 150 to 550ºC for the inner tube, and from 20 to 150ºC for the outer tube. The temperature range could be displaced up or down, adapting detectors sensitivity. Higher temperatures could be measured, but in this case accuracy would be lost for low temperatures. The selected range has been chosen in order to accurately cover current operation modes of parabolic trough technology.

The new thermometer is designed to survive daily use in a solar plant extreme environment: high temperature, dust, possible shocks, etc. It is a compact portable device with robust mechanical and electronic configuration to minimize damages. It is conceived for use as an operation and maintenance instrument but also provides valuable data for research and development.

Calibration

The device just requires an initial laboratory calibration, not needing repeating calibrations in the daily use. For this purpose, a laboratory experimental calibration curve signal-temperature is obtained. A receiver tube is placed on a test bench equipped with a heating system which allows maintaining a homogeneous and constant tube temperature which is controlled by k-type thermocouples. The detectors readings registered in the experimental calibration matched with the theoretical values obtained from Planck's Law.

Measurement process

Switch on the measuring unit and the control unit. Place the measuring unit above the evaluated tube so that the device case is correctly positioned around the glass envelope. The analog signal from detectors is processed and digitized. The digital signal is converted to temperature using the calibration curves. Values of the six temperatures, three from each tube, are shown in real time at the control unit screen and can be captured and saved.

PERFORMANCE EVALUATION

To determine the new thermometer performance a laboratory test was performed as shown in Fig.4. A commercial receiver tube was placed on a test bench equipped with a heating system which used an electrical source to maintain a homogeneous and constant set-point temperature in the inner metallic tube. To do so, K-type thermocouples with an accuracy of ±0.3% value +1ºC, are introduced along the tube and a PID controller converges the measured temperature and the set-point temperature. Both values are shown in a real time display. Laboratory ambient temperature and humidity are continuously controlled and also showed in a display.

During the test, the inner tube set-point temperature was fixed and kept constant, repeating the process for three temperatures: 200, 300 and 400ºC. Two K-type thermocouples were used to monitor the glass temperature, connecting then to a Chauvin Arnoux C-A 863 thermometer, resulting a system with accuracy ±0.3% value +1ºC. One thermocouple was placed on one side and the other on the top of the glass tube.

A Flir Systems Thermacam P25 was used to monitor the glass temperature. It measures the far infrared, in particular 7.5-13 µm and with an accuracy of ±2ºC or ±2%. This camera required the image center spot to coincide with the evaluated body and its emissivity had to be manually introduced, being fixed at 0.88 for this test.

And lastly, a Flir SC 7000 thermal camera was used to separately monitor both tubes temperature. It evaluated the medium infrared, in particular 1.5-5.1 µm with an accuracy of ±1ºC or ±1%. This camera required an electrical outlet and also connection to a computer from which the camera was controlled and the image analyzed. Different filters in the camera allow narrowing the analyzed spectrum. Just one filter can be used at a time. The 4.6-5.1 µm filter was used for the outer tube and the 2.36 µm filter for the inner tube. Images were taken looking towards the tube from the side at 1.5 meters. Emissivity was fixed at 0.88 and 0.5 for the outer and the inner tube evaluation, and the temperature was taken as the average of the tube cross section.

(a) (b)

FIGURE 3. Laboratory test comparing multiple instruments (a), and new thermometer (b)

In Table 1 the outer tube temperature measurement with each instrument are shown. Similarly the inner tube temperature measurements are shown in Table 2.

TABLE 1. Glass temperature value (ºC) obtained with the different instruments for the three evaluated inner tube temperature

Instrument	200ºC	300ºC	400ºC
New thermometer top measure	35.3	51.5	69.5
New thermometer side measure	34.9	48.3	66.1
Thermocouple top	36	50.7	70.4
Thermocouple side	35.6	49.1	67.4
Flir SC 7000 (cross section)	38.5	52.5	72.6
Flir P25 portable pointing to the side	40	49.9	62.1

TABLE 2. Inner tube temperature value (ºC) obtained with the different instruments

Instrument	200ºC	300ºC	400ºC
New thermometer top measure	202.8	298.5	398.3
New thermometer side measure	202.5	298.3	398.4
Thermocouples (*)	200ºC	300ºC	400ºC
Flir SC 7000 (cross section)	Out of range	Out of range	407

(*) Thermocouples are the same used to control the tube heating system controller.

Uncertainty of the measurement

Quality of the measurement is evaluated by calculating its uncertainty [14]. For that purpose one commercial receiver is evaluated using 100 measurements with the new thermometer. This evaluation was carried out in a laboratory with ambient stationary conditions and with no fluid flowing through it. A test bench equipped with a heating system was used to maintain a homogeneous and constant temperature of 400ºC in the inner metallic tube.

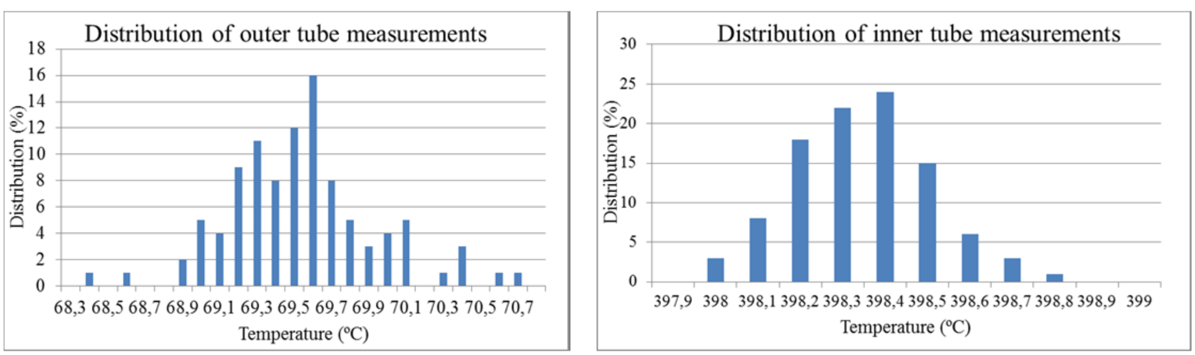


FIGURE 4. Uncertainty test

The distributions of the obtained results are shown in Fig.5 for both temperatures measured. The average values were T=69.5 ºC for the outer tube and T=398.3ºC for the inner tube. The uncertainty type a (absolute value) of the device, which related to precision or repeatability, has been calculated from these 100 readings resulting in the following values for both sensors. The uncertainty type b was calculated from the uncertainty of the thermocouples used to calibrate the thermometer. This value is 0.3 (absolute value) at a level of confidence of 95% (k=2).

$$u_{A,outer} = 0.6\ \% \qquad u_{A,inner} = 0.04\ \% \qquad u_{B,outer\ and\ inner} = 0.15$$

The standard combined uncertainty is calculated as:

$$u_{C,outer=} \sqrt{{u_{A,outer}}^2 + {u_{B,outer}}^2} = 0.6 \qquad u_{C,inner=} \sqrt{{u_{A,inner}}^2 + {u_{B,inner}}^2} = 0.15 \tag{4}$$

According to these results, the expanded uncertainty expressed in absolute values at a level of confidence of 95% (k=2) is:

$$u_{outer} = 1.2\ \% \quad u_{inner} = 0.3\ \%$$

Defining the term accuracy as the difference between the real value of a parameter, and the value provided by a given measuring device, and based on all laboratory test results, it can be affirmed that for any sensor, both for the outer and inner tubes, and for any temperature within in the specified working range, the accuracy of the new thermometer is ±1%value +1ºC.

BENEFITS OBTAINED IN A SOLAR PLANT

Receivers are designed to withstand exposure to harsh environmental conditions and the rigors of daily operation. However, sometimes, receiver vacuum loss may occur. The vacuum loss can be total due to a glass fracture or breakage of the glass-metal welding, or can be partial with progressive de-gassing through micro-pores.

According to models [5] [10], the tube thermal losses are directly related with the vacuum state. For a given inner tube and ambient temperature, the glass temperature is an indication of the vacuum state. Using these models a threshold glass temperature can be defined to determine if the vacuum conditions and consequent thermal losses meet a performance threshold. An example of a non-conservative equation obtained from these models is.

$$T_{glass\ threshold}\,(^{\underline{o}}C) = T_{ambient}(^{\underline{o}}C) + 40 + \frac{(T_{inner\ tube}\,(^{\underline{o}}C) - 240)}{3} \qquad (5)$$

The new thermometer described here allows simultaneous measurement of the glass tube, inner tube and ambient temperatures of any receiver tube installed in the solar field, which makes it the first specific measuring instrument to easily and instantly determine a receiver's thermal performance during operating conditions. The plant average performance relative to this parameter can be known and used for production planning [7]. Plant operation and maintenance [15] can be optimized by replacing those tubes which do not meet the performance threshold.

Commercial parabolic trough STE plants are composed of thousands of receivers grouped in hundreds of solar collector assemblies (SCA). To control and optimize STE plant operation, the temperature of the HTF is monitored at several points of the plant. This monitoring is done using thermocouples. The more measuring points installed in the plant, the more detailed and localized the performance information. Commonly thermocouples are placed in the inlet and outlet point of a SCA.

During operation, a performance decrease can be detected in a specific SCA, which could be caused by different reasons such as tracking errors, mirror reflectance, tube transmittance decrease or tube vacuum loss. In this case, the new thermometer would represent a useful tool to analyze tube by tube the thermal performance of a specific SCA. Also anomalous readings from thermocouples can be caused because they are out of calibration, which could also be rapidly detected with the thermometer.

MEASUREMENT STUDIES IN THE SOLAR FIELD

The presented thermometer has been tested in STE plants. As an example, results from an evaluation carried out in a research pilot plant in Sanlúcar la Mayor, Spain are shown.

A total of 45 random tubes from 10 SCAs were evaluated using two instruments: new thermometer and Flir P25 portable camera. Tubes were evaluated during plant operation. While the SCA was being evaluated, it was partially defocused as concentrated light prevents proper camera operation. For the camera the image center spot was pointed at the front of the tube from a distance of 2 meters. The thermometer was just positioned around the tube using the special pole.

During the evaluation, data from the SCA thermocouples were collected to compare them with the inner tube temperature measured with the thermometer. Note that these sensors are placed at the SCA inlet point so small differences from the evaluated tube are expected.

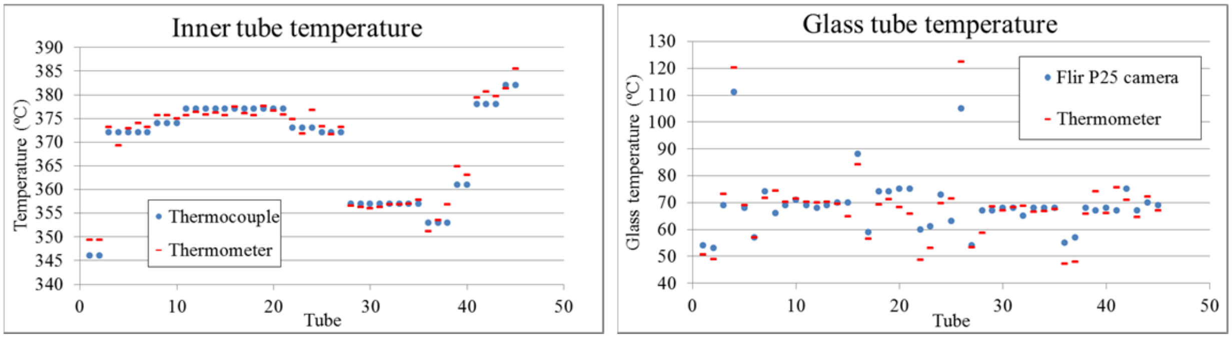


FIGURE 5. Results for the solar plant evaluation

It can be seen a high level of correlation between the inner tube temperatures measured by the thermometer and the SCA thermocouple reading, with differences lower than 4ºC in most cases. It confirms the accuracy determined in the laboratory.

Regarding the glass temperature, there are sometimes higher differences between thermometer and thermal camera, and it is more evident at high temperatures, something also noticed in the laboratory test. In spite of the fact that tubes tested in the same SCA represent the same inner tube temperature, a large variability of the glass temperature can be seen.

Useful data obtained with the thermometer in this plant evaluation is the detection of tubes with total vacuum loss. Applying equation (5) to data collected from the new thermometer it can be verified that tubes number 4 and 26, which presents glass temperature of 120 and 122 ºC have lost vacuum.

$$T_{threshold} = 30 + 40 + \frac{370 - 240}{3} = 113\ ºC$$

CONCLUSION

A novel portable device to simultaneously measure the temperature of both the inner metal and the outer glass tubes of parabolic trough receivers has been presented. The designed measuring principles, patent pending P201431969, based on the combination of the receiver's optical properties and the emissive spectral power from each tube at operating temperatures, allow performing non-contact measurement of the temperature of both tubes. The new thermometer is a unique compact and portable device which no adjustments, external connections, wires or daily calibration requirements. It integrates the features for which until now two measurement systems were necessary, assuring for both temperatures an accuracy of ±1% value +1ºC. The working range covers all operating temperatures for parabolic trough solar plants.

The presented device is the first specific measurement instrument which offers a technical solution for the evaluation of the thermal performance of parabolic trough receiver tubes installed in a plant. This provides data on an influential parameter in the solar plant performance model. Therefore, as it has been already proved by use in solar plants, the new thermometer provides a useful tool for plant operation enabling an accurate characterization of any point of the plant during operation, measuring its performance or detecting tubes which do not meet a thermal performance threshold. Also maintenance work to optimize the solar field can be done thanks to the detailed information obtained.

It has a robust and light weight mechanical and electronic design to make it a suitable instrument to work outdoors in the field. Measurement is convenient and instantaneous. The measuring unit is wirelessly connected to the control unit, equipped with battery and memory and with backlighted keyboard and screen where temperatures are shown in real time. It can be also be controlled using a custom developed mobile phone application.

REFERENCES

1. Andreas Poullikas. Economic analysis of power generation from parabolic trough solar thermal plants for the Mediterranean region. A case study for the island of Cyprus. Renewable and sustainable Energy reviews. 13 (2009) 2474 -2484.
2. Stephanie Meyen ... [et al.]. Standardization of Solar Mirror Reflectance Measurements--Round Robin Test Preprint. [Golden, CO]:National Renewable Energy Laboratory, 2010.
3. J.L.Navarro, N.Martinez. Receiver tube performance depending on cleaning methods. (Energy Procedia Volume 69, May 2015, Pages 1529–1539)
4. G.Espinosa, N.Martinez. A Novel Portable Device to Measure Transmittance and Reflectance of Parabolic Trough Receiver Tubes in the Field, ASME 2014, ES2014-6500
5. Forristal R. Heat transfer analysis and modeling of parabolic trough solar receiver implemented in engineering equation solver. NREL Technical Report. 2003, NREL/TP550-34169.
6. Price, H.,. A Parabolic Trough Solar Power Plant Simulation Model. 2003 Report No. NREL//CP-550-33209,
7. Andrea Giostri, Marco Binotti, Marco Astolfi, Paolo Silva, Ennio Macchi, Giampaolo Manzolini. Comparison of different solar plants based on parabolic trough technology. Solar Energy 86 (2012) 1208–1221
8. Fritz Zaversky, Javier García-Barberena, Marcelino Sanchez,. Probabilistic modeling of a parabolic trough collector power plant – An uncertainty and sensitivity analysis. Solar Energy. 86 (2012) 2128 -2139.
9. Kennedy C.E. Review of mild to high temperature solar selective absorber materials. NREL Technical report. NREL/TP-520-31267.
10. Frank.P. Incropera ,Fundamentals of Heat and Mass Transfer.
11. M. Pfänder, E. Lüpfert y P. Pistor “Infrared temperature measurements on solar trough absorber tubes” (Solar Energy, Vol. 81, Is. 5, pp 629-635, 2007)
12. Henry Price, Russell Forristall, Field Survey of Parabolic Trough Receiver Thermal Performance, 10.1115/ISEC2006-99167, ASME 2006 International Solar Energy Conference
13. ASTM G 173-03; Terrestrial Reference Spectra for Photovoltaic Performance Evaluation.
14. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, OIML, The International Vocabulary of Metrology, Basic and General Concepts and Associated Terms - VIM, JCGM 200:2008 [ISO/IEC Guide 99]
15. Cohen et al, “Final report on the operation and maintenance improvement program for concentrating solar power plants”, SAND99-1290 Unlimited Release, June 1999