Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy

FP7 Grant Agreement number:	**609837**
Start date of project:	**01/02/2014**
Duration of project:	**48 months**

Project Deliverable 11.7:

Guidelines for the analysis of vacuum-status of receiver pipes by non-contact measurements

WP11 – Task 2.2	**Deliverable 11.7**
Due date:	**January 2017**
Submitted	**January 2017**
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Document version:	**1**
Reviewed/supervised by:	
Dissemination Level	**Public**

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Nomenclature

Acronyms

PTC	Parabolic Through Collector
HTF	Heat Transfer Fluid
IR	Infra Red

Latin Symbols

T	Temperature (ºC)

Subscripts

TH	Measured with thermocouples
IR	Measured with IR camera without calibration
IRc	Measured with IR camera and calibrated with thermocouples
Lab	Measurement performed in laboratory
Field	Measurement performed on field

1. Introduction

Receivers of parabolic through solar collectors (PTC) are designed to absorb the energy of the concentrated solar radiation and to transfer it like thermal energy to the heat transfer fluid (HTF) circulating inside.

To improve the performance of the process is needed to minimize thermal losses as much as possible. To that end, the PTC receiver is composed by a steel tube (the absorber) with selective coating, having high solar absorptance and low thermal emittance. To avoid thermal losses by convection on the absorber tube there is a concentric glass envelope to maintain vacuum conditions in the ring between the absorber and the glass envelope as shown in **¡Error! No se encuentra el origen de la referencia.**. The steel and glass tubes are connected with a metal-glass welded elbow which has been designed to compensate the difference thermal expansion of two materials. In order to reduce the thermal loses and avoid the oxidation of the selective coating the air of the annulus between the two tubes is evacuated.

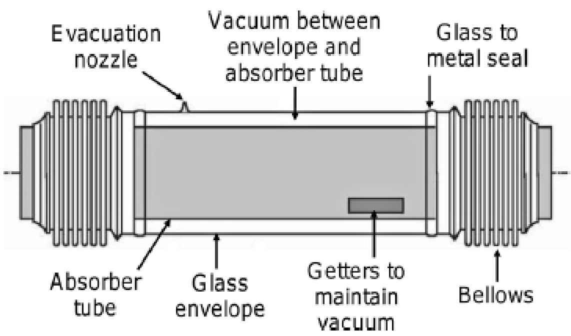

Figure 1 Components of an absorber tube of parabolic trough collectors

Unfortunately, the loss of vacuum is one of the most common PTC receiver failures and has a direct impact in the Solar Thermal Energy plant (STE) performance. Hence the predictive maintenance of the PTC receivers of large parabolic through solar fields is a key issue. It is required a vacuum status checking system that, if possible, allows the continuous operation of the solar fields. In response to this concern three methods have been developed until now: the stationary method, the quasi-stationary method and the surface temperature method. From these methods only the last one has been developed for field inspection. The other two methods are appropriate for laboratory measurements [1][2] and therefore will be not considered in this work.

Regarding the **surface temperature method**, it is based on the fact that the glass temperature increases when the vacuum is lost because of the increase of thermal losses by convection on the absorber. This means that in theory, and for a given atmospheric condition, it is possible to determine the vacuum level from the glass and the absorber temperature measurements. The temperature of the glass surface can be measured with non-contact methods (e.g. thermographic cameras or pyrometers) and the temperature of the absorber can be determined with 3 different approaches: a) considering the temperature of the metal equal to the average temperature of the HTF, b) relating the linear expansion of the metal with its average temperature, and c) by means of non-contact methods like thermographic cameras or pyrometers.

The surface temperature method has been validated as powerful tool to determine the vacuum qualitative status (e.g. with vacuum or without vacuum) of a PTC receiver, however it has not been validated yet for a quantitative vacuum status estimation. The estimation of the quantitative vacuum level will open the doors to more accurate failure predictions.

In this work it is explored the possibility to extend the surface temperature method to estimate the vacuum level of the receiver tubes. This work has been carried out within the frame of the European project STAGE-STE, (Work package 11, Subtask 11.2.2-thermal inspection working group). Test campaign has been completely designed and performed by the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) at the Plataforma Solar de Almería (PSA) facilities (HTF test loop and the Solar linear Receivers laboratory) in Spain.

2. Methodology

The experimental campaign has been designed to relate the glass temperature with the vacuum quantitative status. For that purpose the experiments has been carried out in laboratory conditions and on field conditions. On one hand, the laboratory experiments minimize the effect of the uncontrolled atmospheric conditions which will allow to minimize the dispersion of the results and its better understanding and, on the other hand, the on field experimental campaign has been designed (based on the results of the laboratory campaign), to study the applicability of the technic on a real PTC plant.

2.1. Laboratory experimental campaign

The laboratory experimental campaign has been designed to obtain the glass temperature as function of vacuum level in the annulus between the absorber and the glass envelope for different absorber temperatures. The glass temperature have been measured at 5 vacuum levels (10^{-4}, 10^{-2}, 100, 10^{2}, 10^{3} mbar) and 4 different absorber temperatures (100, 200, 300, 350 and 400 ºC). All the experiments were performed in steady state conditions, i.e. assuring constant ambient and receiver temperature (temperatures of glass envelope and absorber surfaces), and constant vacuum in the annulus between the glass and metal tubes. Each measurement point is extracted from data recorded during ten minutes with a sampling time of 1second. Moreover to obtain good statistic results the experimental campaign was repeated 3 times in different days.

The experimental setup consisted in a single PTC commercial receiver to which a hole has been done to control de vacuum in the annulus between the absorber and the glass envelope. The receiver can be heated and pressurized at suitable test conditions. *Figure 2* and *Figure 3* show the schematic view and the aspect of the experimental set up. The main components are described below:

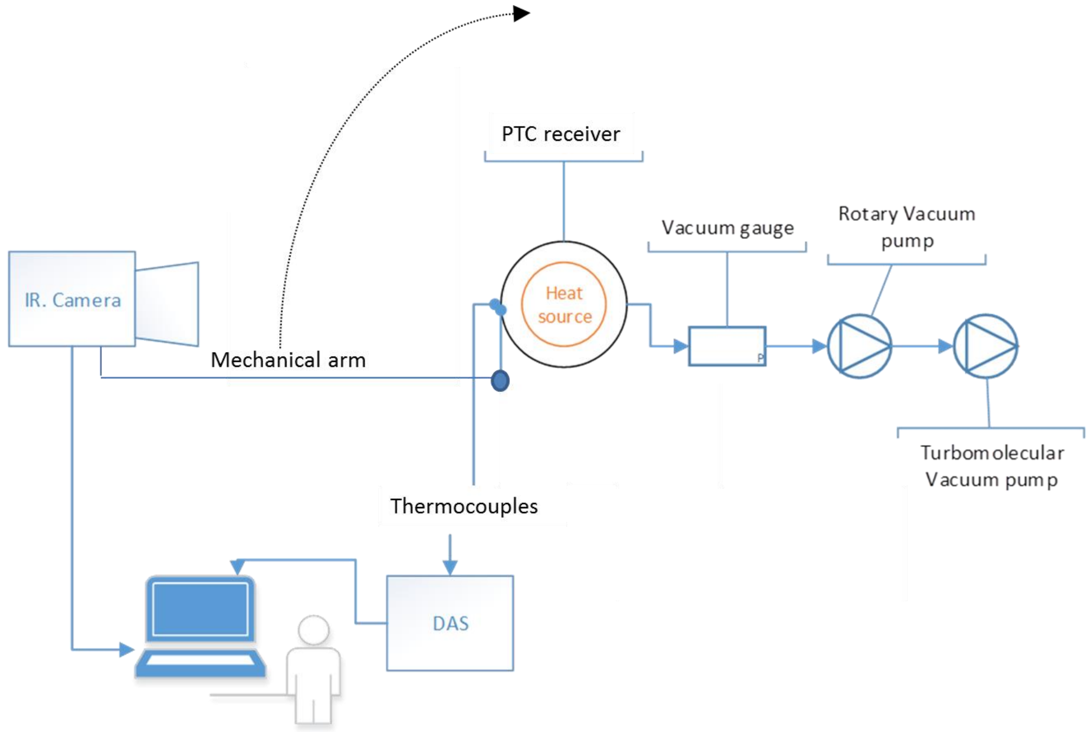

Figure 2. Schematic view of the laboratory experimental setup.

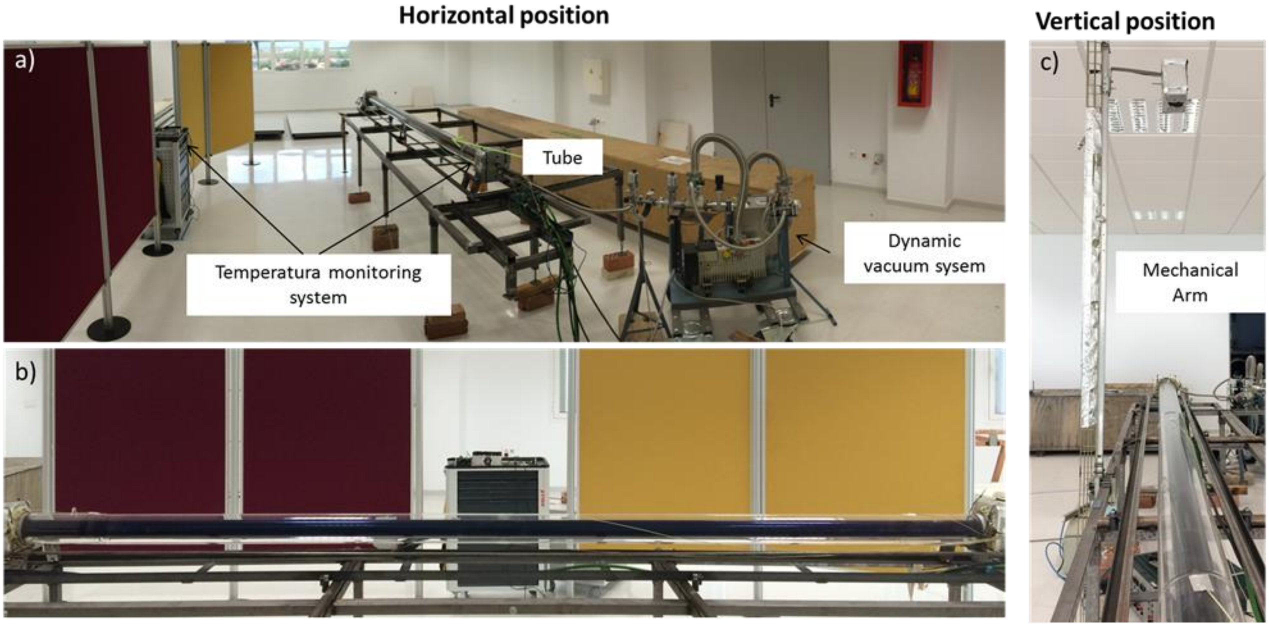

Figure 3. Laboratory experimental setup. a) lateral view, b) front view, c) lateral view with the mechanical arm in the vertical position

Vacuum system: It is composed of two vacuum pumps connected in series to the tube receiver, one rotary Balzers Duo 004B pump (maximum pressure 10^{-4} mbar) and one turbo-molecular vacuum pump model Pfeiffer TMU 071 P (maximum pressure $5 \cdot 10^{-10}$ mbar). The vacuum system is running throughout the test at constant pressure. Vacuum measurement in the tube receiver is done with two Pirani gauges manufactured by Pfeiffer. One of them is model PKR 251 (pressure range of 5·10-9 to 1000 mbar) and the other one is model TPG 201 (pressure range from 5·10-4 to 1000 mbar).

Heating system: This system supplies thermal energy to the receiver tube. An aluminum cylinder (4.06 m-long and 0.055 m-diameter) is heated by 8 electrical heaters of ~6.3 Ω/m inserted in 8 grooves along the outer side of the aluminum, which are connected to 2 electrical power supplies (4 electrical heaters connected in parallel by power supply) and controlled independently but providing the same power per electrical heater. In addition, 2 extra small electrical heaters of ~750 Ω are inserted in respective ends of the cylinder and controlled by 2 other independent power supplies, to counteract the edge effect and the consequent temperature drop in the absorber ends.

All the electrical power supplies are N8740A model manufactured by Agilent Technologies. These electrical powers can supply a maximum of 3300 W (150 V, 22 A) DC each one.

The aluminum cylinder with the electrical heaters is inserted inside the absorber tube, heating it by radiation and convection

Temperature monitoring system: The temperature is measured with contact and non-contact techniques. On one hand the temperatures of absorber tube, glass envelope and ambient temperature are measured using type K-class I thermocouples. The angular distribution of temperature has been measured considering as reference the top of the tube as

0°, the middle position as 90° and the bottom position as 180°. A total of 24 thermocouples are located as follows:

- 14 thermocouples measure the temperature of the inner wall of the absorber tube; half are placed on top, at 0.10 m, 0.30 m, 1.00 m, 2.03 m, 3.06 m, 3.76 m and 3.96 m, and half at the bottom in the same position.

- 7 thermocouples measure the temperature distribution in the glass envelope surface; 3 placed on top at 0.10 m, 2.03 m and 3.96 m, 3 at the bottom again in the same position and 1 in middle at 2.03 m.

- 1 thermocouple measures the ambient temperature.

Additionally, the glass envelope surface temperature has been monitored using radiometric method based on the norm ASTM E2847-14. For that purpose an IR camera (Optris Pi640) has been used. This camera has an accuracy of ±2 °C and a temperature resolution (NETD) 0.075°C within the 7.5-13 µm spectral range. The camera has been equipped with a super wide angle lenses (90^ox66^o). This configuration allows monitoring 3 meter of the tube at a short distance (1.5 m) with a pixel size of 5x4 mm. The camera has been mounted on a mechanical arm that allows it to move from horizontal to vertical position and acquire IR images of the top (0°) and middle (90°) position of the PTC receiver. The IR images of the bottom position of the tube have not been acquired due to the geometrical restrictions of the test bench.

Temperature obtained from IR images (T_{IR}) has been calibrated with the temperature data obtained with the thermocouples (T_{TH}). The calibrated T_{IR} will be named T_{IRc}. T_{TH} has been defined as function of T_{IR}, and the calibration function is obtained of the lineal fitting obtained as $T_{IRc} = T_{TH}(T_{IR})$.

T_{IR} has been defined as the temperature measured by de camera at the same angular position of the thermocouples (0° and 90°), when the surface emissivity is supposed to be 1.

Moreover, the temperature distribution of the cross section, shown in *Figure 4*, has been analyzed from calibrated IR images.

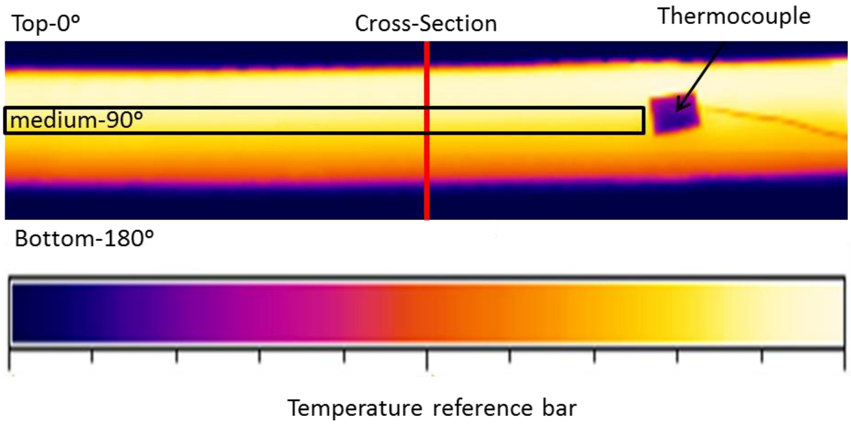

Figure 4. Non calibrated IR images of the PTC receiver acquired at 90° from the horizontal position and the area used (black rectangle) to estimate the temperature of glass at equivalent position of the thermocouple.

Data acquisition system and SCADA: All the thermocouples are connected to a data acquisition system composed of a data logger model Data Taker DT85 (48 analog inputs plus 12 flexible digital channels) with an expansion module CEM20 (20 universal data logging channels). Voltage and DC current supplied to the heating system are measured by the electrical power supplies.

All the equipment and sensors of the test bench, except of the IR camera, are monitored and controlled from a workstation with a Supervisory Control and Data Acquisition system (SCADA) developed and implemented using Lab VIEW. The IR camera measuring data are recorded and stored in a Lenovo L460 laptop and post analyzed with Optris Pi connects software.

Mechanical arm: A mechanical arm moves the camera between the horizontal positions to the vertical position to acquire thermal images from both positions at the same distance of the glass envelope surface.

2.2. On field experimental campaign.

The accuracy of the relation (glass temperature-vacuum level) obtained under laboratory conditions have been tested in the HTF test loop facility at the PSA under solar real operation conditions. Two tubes of the same model that the one tested under laboratory conditions, one of them with vacuum and the other one with the vacuum lost (10^{-4} mbar and 10^{3} mbar), have been selected and characterized. The characterization of the tube receivers includes the measurement of the glass at different absorber temperatures (100, 200, 250, 300 and 350^{o}C).

The on field experimental configuration is similar to on the laboratory. In ***¡Error! No se encuentra el origen de la referencia.*** and *Figure 6* can be seen the main components described below:

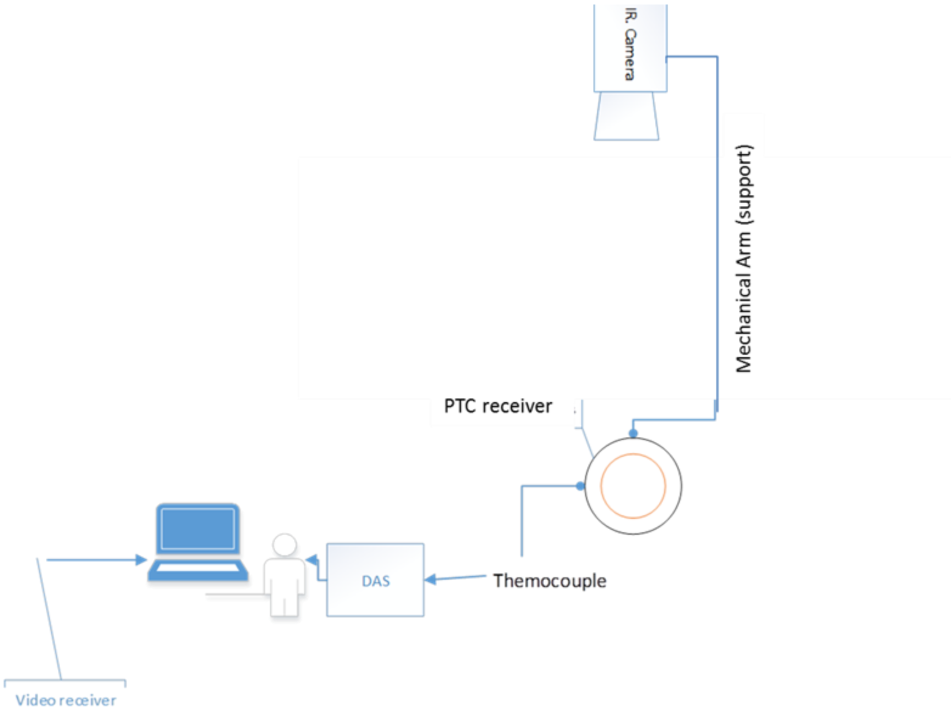

Figure 5. Schematic view of the of field experimental setup.

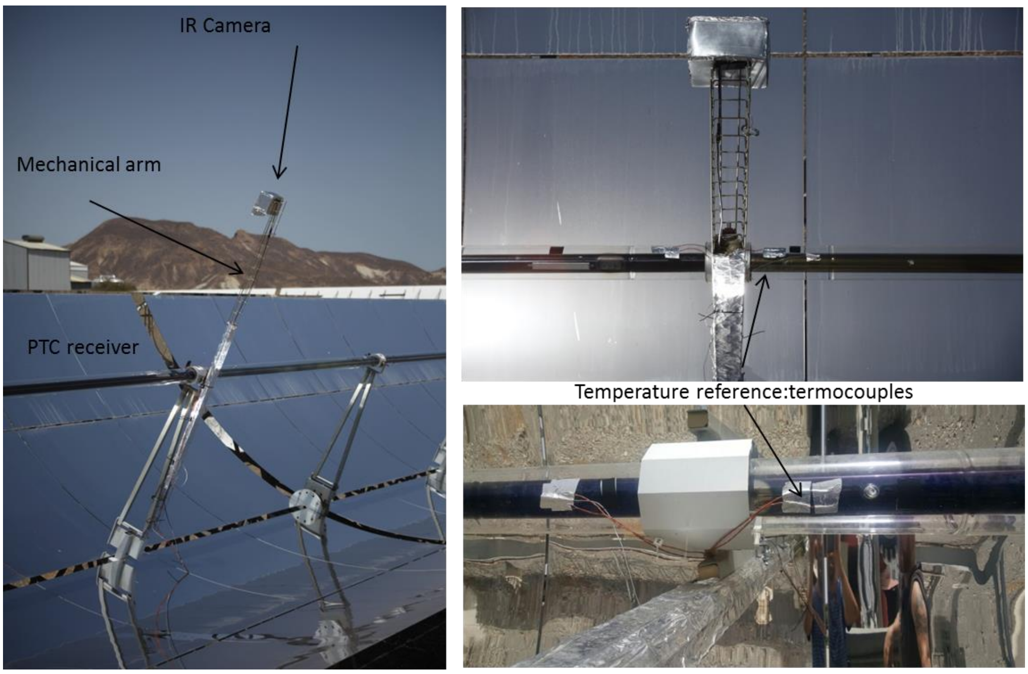

Figure 6. Aspect of the field experimental setup.

Temperature monitoring system:

- IR camera: It was used the same IR camera that the one used in the laboratory. It was installed at 1.3 meter of the receiver tube in the same mechanical arm used in the laboratory experimental setup to acquire images of the non-irradiated side of the receiver tube. This position is equivalent to the vertical position (0°) of the laboratory experimental setup.

- Contact temperature sensors: The glass temperature was measured in the non-irradiated side with 5 T-type thermocouples. Moreover the temperature of the absorber was considered equal to the HTF temperature measured with 4 PT-100.

Data acquisition system: The thermocouples signals were recorded with a portable data logger (Graphtec gl200 midi logger) and the PT-100 data were recorded with a IMP 359555 J data acquisition system. The IR camera measuring data are recorded and stored in a Lenovo L460 laptop and post analyzed with Optris Pi connects software.

3. Results

Below is shown the laboratory experimental campaign results and the on field measurements.

3.1. Laboratory experimental campaign

The glass temperature as function of absorber temperature and annulus pressure levels has been analyzed from the data obtained with thermocouples and IR camera.

Figure 7 shows the glass temperature at a) top, b) medium, c) bottom position and d) temperature difference between the top and the bottom as function of annulus pressure level for different absorber temperatures. As can be seen, the temperature of the top and medium position increase when the pressure or the absorber temperature increase. On the other hand the temperature of the glass at the bottom increases with pressures from 10^{-4} mbar to 10^{0} mbar and decreases from 10^{0} mbar to 10^{3} mbar.

Regarding the temperature difference between the top and the bottom, the temperature at the top is always higher than in the medium and bottoming position with indicates that there is always a thermal gradient in the glass. This thermal gradient increases with absorber temperature for all the pressure range. Moreover it remains almost constant with pressure from 10^{-4} mbar to 10^{2} mbar and increase faster from 10^{2} mbar onwards.

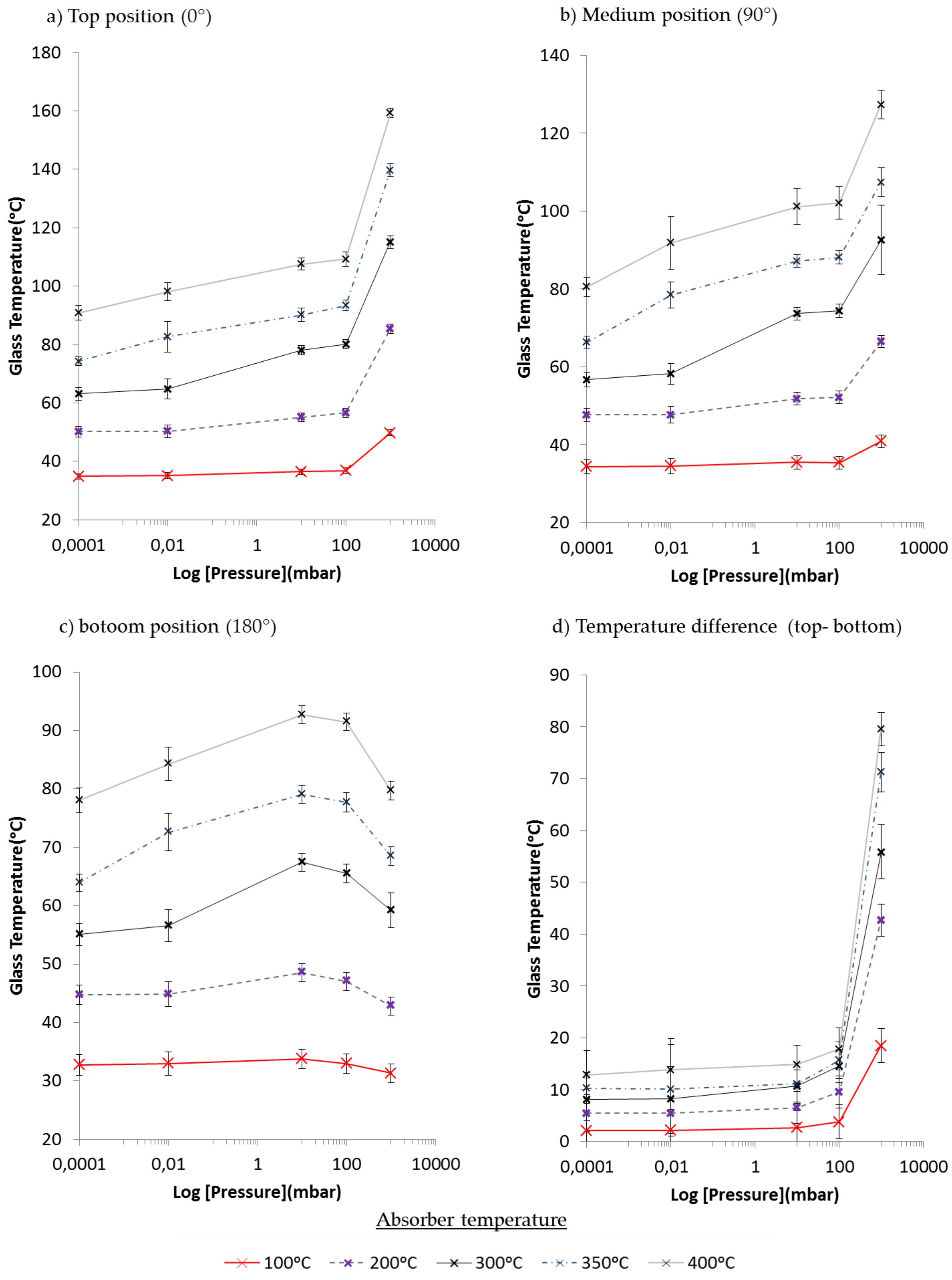

Figure 7 Glass temperature at a) top, b) medium, c) bottom position and d) temperature difference between the top and the bottom as function of annulus pressure (from 10^{-4} mbar to 10^{2} mbar) level for different absorber temperatures from (100 °C to 400 °C).

These observations suggest that the mechanism that produces the thermal gradient is different above and below 10^2 mbar. There are two possible mechanisms that produce the thermal gradient; the free convention of the external air and/or the convention and stratification of internal air. Taking into account that the convention of the internal air increase from 10^2 mbar and above [3] it seems that the thermal gradient above 10^2 mbar is due mainly to this mechanism.

The temperature data obtained with the thermocouples (T_{TH}) has been used to calibrate the temperature obtained from IR images (T_{IR}) which will be named T_{IRc}. To that end T_{TH} has been defined as function of $T_{IR,}$ by means of lineal fitting shown in *Figure 8* and the calibration function has been obtained as $T_{IRc} = T_{TH} (T_{IR})$. In *Figure 8* $T_{TH} (T_{IR})$ shows good linearity at 0° and 90°. However the coefficient of determination R^2 is slightly higher at 0° (R^2=0.98) when compared to 90° (R^2=0.94).

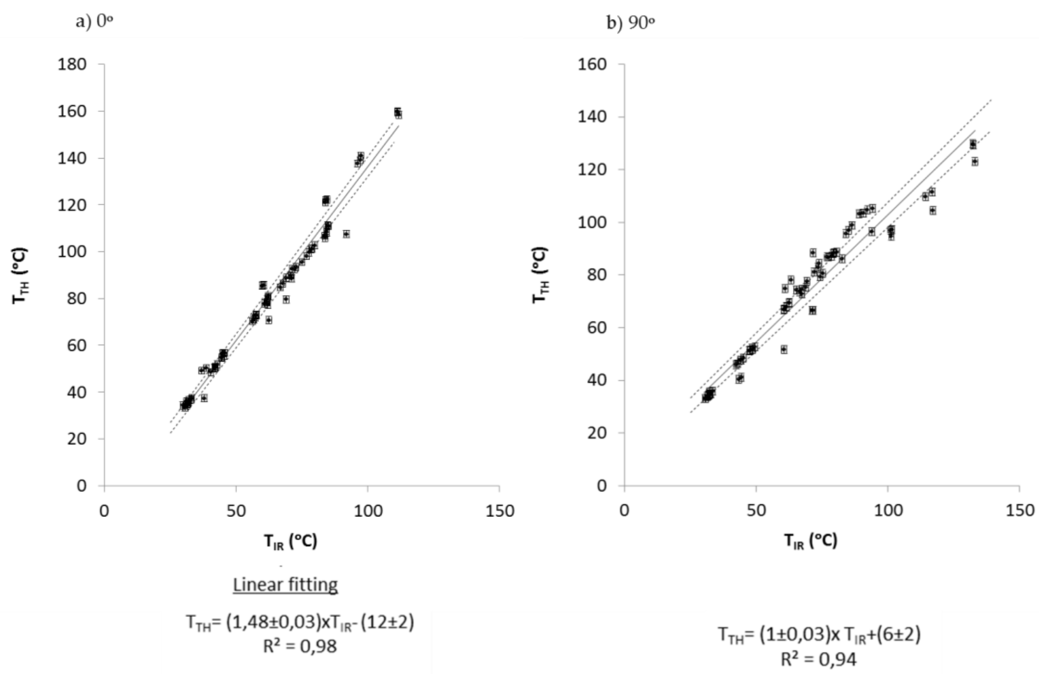

Figure 8. Temperature data obtained with the thermocouples (T_{TH}) as function of the temperature data obtained from IR images (T_{IR}) and its lineal fitting.

This calibration function has been used to obtain the T_{IRc} of the glass as function of absorber temperature at 0° and 90° as it is shown in *Figure 9.*

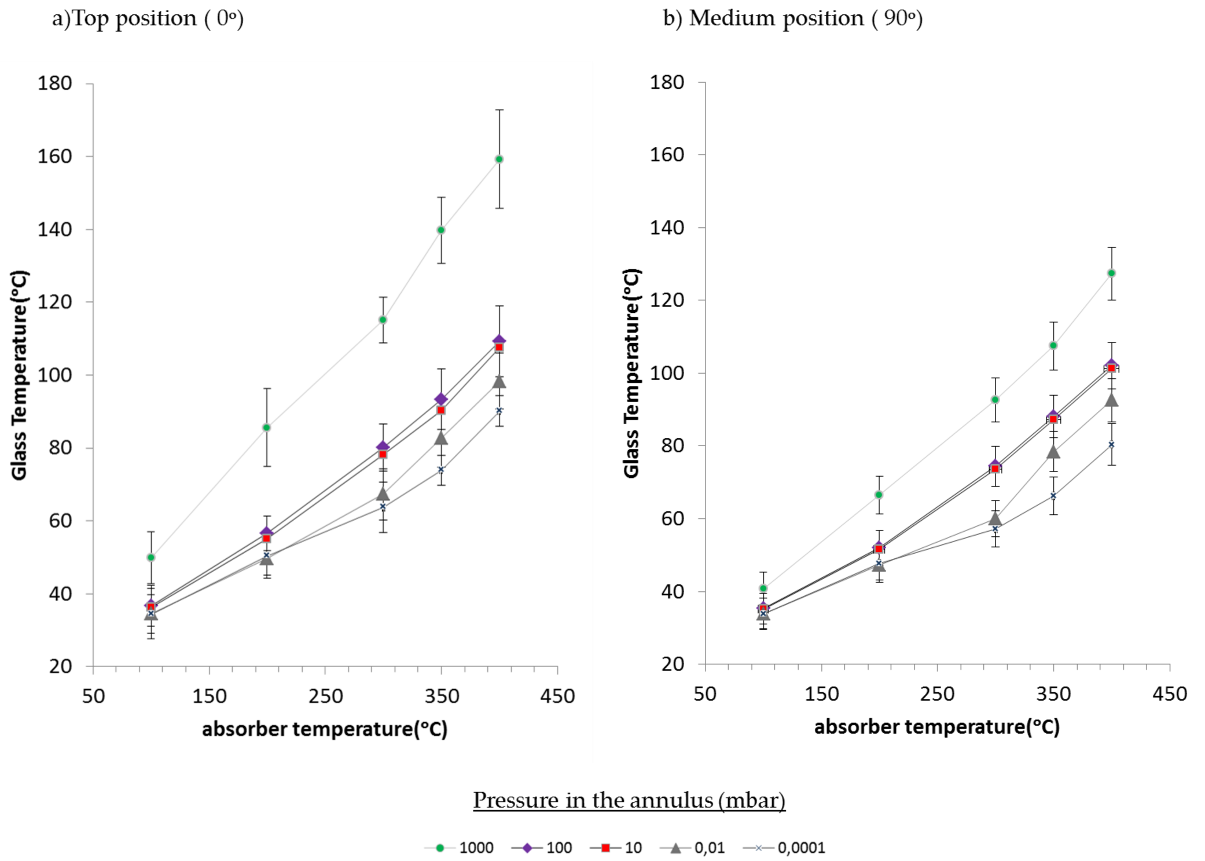

Figure 9. Glass temperature (T_{IRc}) as function of absorber temperature for several pressure levels at a) top position (0°) and b) middle position (90°)

As it was expected from previous results obtained with the thermocouples, the temperature of the glass increase with the absorber temperature and/or the pressure in the annulus. Moreover this results shown that the glass temperature difference between pressure levels (for the same absorber temperature) is low from 10^{-4} to 10^{2} and higher at 10^{3} mbar. This observation suggests that the prediction of the pressure in the annulus from glass and absorber temperature measurements is easy when the vacuum is loss (10^{3} mbar) and requires higher precision when the pressure is from 10^{-4} to 10^{2}.

Furthermore the glass temperature difference between pressure levels (for the same absorber temperature) is higher at 0° than at 90°. This observation suggests that it is easier (less required precision) to deduce the pressure level from glass temperature measurements at 0° than at 90°. This conclusion was considered in the on field measurement where the measurements were carried out only at 0°.

Regarding the temperature profile of the cross section, *Figure 9* shows the results at different absorber temperatures and different pressures (*Figure 9.a*) 10^{-4} mbar and *Figure 9.b*) 10^{3} mbar). At low pressure (10^{-4} mbar) the measured glass temperature profile shows low temperature and high tilt in both corners and higher temperature and low tilt in the center of the tube. Considering previously results obtained with the thermocouples, it was not expected such a temperature distribution in the proximity of both corners. In order to understand the temperature profile in the proximity of the corners it must be taken into account that the emissivity of the glass has been consider as constant for all the surface, neglecting its directionality. This approximation is true when the angle between the camera optic axes and surface normal vector is lower than 60°. However the measured surface is rounded and therefore the angle between optical axes of the camera and the normal vector of the surface increase from the center to the corners and from 60° onwards and the irradiance received by the camera decrease fast due directionality of the emissivity [4] The apparent lower emissivity of the surface is translated in a false temperature measurement.

Regarding the true temperature measurement of the central area, it can be seen that the temperature and thermal gradient (slope of the temperature profile) increase with absorber temperature and annulus pressure. These results are in good agreement with the results obtained with the thermocouples.

The temperature profile of glass tube cross section from vertical position is shown in *Figure 10.* As can be seen the IR image acquire from the vertical position have a flatter profile than from horizontal position. The temperature increases from corners to the center where the slope is 0 and the maximum temperature is reached. This flatter profile allows to predict the temperature in the center of the glass with much accuracy that in the horizontal position where the slope is higher. For that reason from now on the results will be presented only for vertical position.

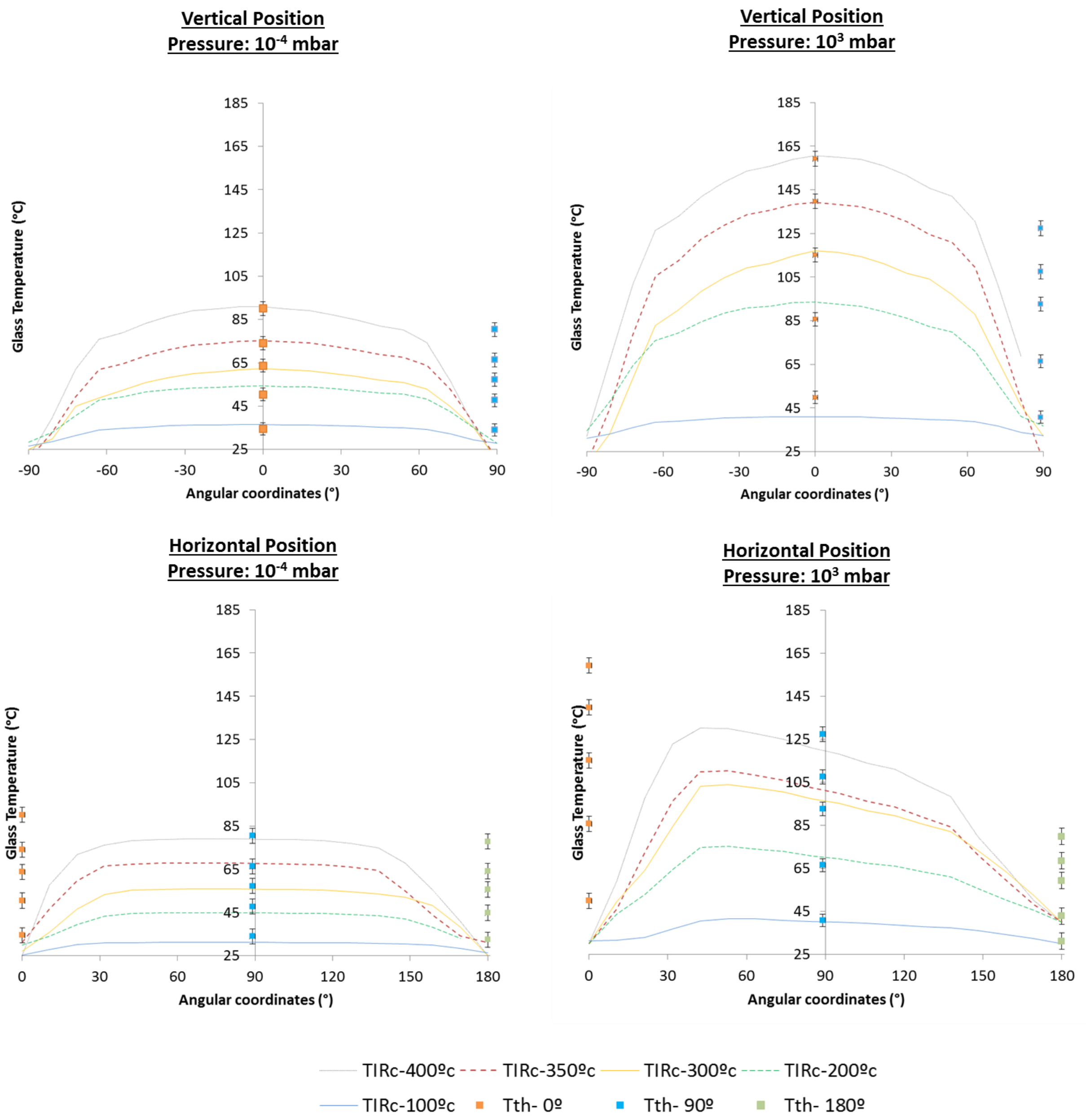

Figure 10. Temperature distribution of the tube cross section obtained from IR images acquired from horizontal and vertical position for various absorber temperatures

3.2. On field measurements.

The previously obtained results demonstrated that pressure in the annulus can be estimated more accurately measuring the glass temperature at 0°. For that reason the on field glass temperature measurements have been carried out only at 0°. These measurements have been carried out in irradiated tubes and non-irradiated tubes. The main difference between both tests is that in the first case the PTC is tracking the sun and in the second case there is not sun tracking and the PTC receivers are heated indirectly by heating the thermal oil with electric coils.

Figure 11 shows the glass temperature measured on field with the thermocouples ($T_{TH\text{-}field}$) and IR camera ($T_{IRc\text{-}field}$) as function of absorber temperature for a non-irradiated and irradiated tube with vacuum (10^{-4} mbar) and without vacuum (10^{3} mbar). Moreover for comparison purpose *Figure 11* shows the glass temperature measured in laboratory with thermocouples ($T_{TH\text{-}lab}$).

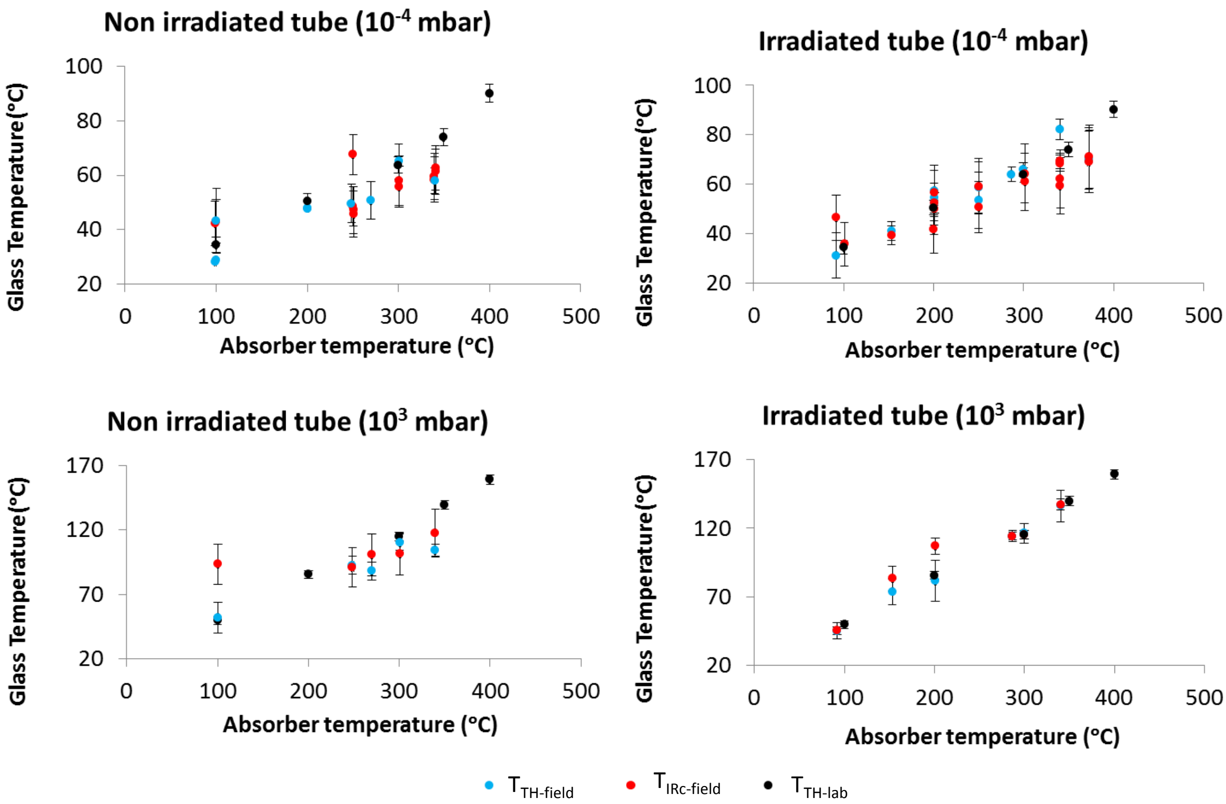

Figure 11. Irradiated and non-irradiated PTC receiver tubes glass temperature as function of absorber temperature.

As can be seen the $T_{TH\text{-}field}$ of irradiated and non-irradiated tubes match pretty well with $T_{TH\text{-}lab}$. These results demonstrate that during the performed test campaign the atmospheric conditions have not of big influence in the glass temperature. Another interesting results is that the glass temperature in irradiated tubes is not higher than in non-irradiated tubes which indicates that this measurements can be carried out during the normal operation of the plant.

In the same way that it was done with the laboratory data, the glass temperature data obtained with thermocouples have been used to calibrate the IR camera images. In order to minimize the effect of changing environment (sky temperature, wind, clouds) the IR images were calibrated with the thermocouples data obtained in the same day. *Figure 11* also show that $T_{IRc\text{-}field}$ is in good concordance with the temperature measured with thermocouples. However the precision is lower in the acquired measurements with the IR camera.

4. Conclusions

Results confirm that the temperature of the glass increase when the vacuum of the annulus is partially or totally lost. This temperature increment is much higher when the vacuum is totally loss (Pressure=10^3mbar) than when is partially loss (10^{-4}mbar <pressure <10^2mbar) regardless of the absorber temperature. This observation suggests that it is easy to deduce if the vacuum is totally lost or not from the glass temperature measurements. However if the vacuum is partially lost, only it is possible to deduce the pressure in the annulus if the uncertainty of glass temperature measurement is lower than the required resolution.

When the glass temperature is measured with an infrared camera in laboratory conditions it is possible to deduce if the vacuum is totally lost or partially lost for the majority of conditions. The required measurement resolution and IR camera measurement uncertainty is lower at 0° than at 90º or/and 180º.Moreover the higher the temperature of the absorber is the lower the required glass temperature measurement accuracy.

On the other hand, when the measurements have been carried out on field, the uncertainty of measurement increased due to changing atmospheric conditions. Therefore it is more difficult to deduce the partial vacuum lost. Moreover contrary to the expected, the temperature of the glass is not affected by the concentrated solar radiation.

Base on this work it is highly recommended to acquire IR images from 0º at maximum HTF temperature as possible when the atmospheric conditions are stable, no matter if the PTC are on tracking or not.

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