High temperature optical fiber transducer for a smart structure on iron-steel production industry

José M. López-Higuera, Francisco J. Madruga, Daniel A. González, Victor Álvarez & Javier Hierro*
Photonics Engineering Group, University of Cantabria
* Global Steel Wire, S.A.
Avda. Los Castros s/n, Santander, SPAIN, E-39005
Phone: +34-942-201498 Fax: +34-942-201873 Email: higuera@teisa.unican.es

ABSTRACT

The quality of the steel, among others, depends on the temperature profile during the last cooling process. Because of that, the capability of real-time temperature measurement at several points of the steel bars during the aforementioned production process is highly desirable in order to build a smart structure. To measure temperatures in the range of 800 –1300 degrees centigrade, the sensor system proposed, is doted of new fiber optic transducers. They are based on the measurement of the optical radiation generated by the hot steel bars through a geometric cavity which is properly designed and fabricated to maximize its accuracy.

Keywords: High temperature transducer, optical fiber transducer, Steel production.

1. INTRODUCTION

It is becoming widely recognized that various types of sensor can be advantageously made using optical fiber either as the medium for data transmission, or as the sensor transducer or both. Fiber optic temperature sensors have several advantages: wide dynamic range, intrinsic immunity to electromagnetic interference and potentially high sensitivity. Among all types of fiber thermometers available today, one of them can be used in practical application for high temperature measurement. This kind of thermometers are based on the Planck's blackbody radiation theorem. The temperature information is obtained by the measurement of the spectral intensity or the intensity distribution [1]. This method is implemented using two techniques.

One the one hand, the transducer is in contact with the target material, and the temperature is measured using a blackbody cavity created onto the end of the optical fiber. Its main disadvantages are the thermal limits of both the material used to make the blackbody and the crystal optical fiber. Its main advantage is the accuracy of the measurement.

On the other hand, it can be found the non-contact technique. The transducer possesses the ability to transmit the captured infrared signal emitted by the target, even when a considerable distance exists. In this case, the compounds used for the transducer are not thermally critical, but the temperature measurement depends on the external conditions and the physical properties of the target material.

In this paper, a non-contact multi-point optical fiber temperature system applied to the measurements of the temperature during the cooling of the steel bar production process is introduced. The fiber transducer harmonizes the aforementioned two techniques. The optoelectronic unit uses typical detectors of optical communications reducing its cost. The system maintains the main advantages of the optical fiber thermometer and it adds both the high accuracy in the useful range and a reduced cost.

2. THEORY OF OPERATION

Heat radiation is a form of electromagnetic radiation and one of the thermal transfer ways (conduction, convection and radiation). The main difference among them is that, meanwhile in the thermal conduction or thermal convection a material substrate is necessary for an energy transfer, thermal radiation occurs in the vacuum and can be observed through surfaces which are transparent in the spectral range of detection. That difference means that the possibility of guiding the radiation emitted by a heated object through a fiber exists and can be used in order to develop a temperature sensor.

Electrically charged particles and neutral particles which compound atoms are always moving, vibrating or rotating, and temperature is a measure of the degree of movement. Higher temperature produces greater agitation and, therefore, all matter, when heated, radiates energy as an amount dependent on the object temperature and its ability to radiate (emittance).

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Close to the radiation idea, a blackbody is a surface which absorbs all the incident energy independently of its incoming direction or its wavelength and, consequently, it neither reflects nor transmits. In the same way, it is possible to define the blackbody as a perfect radiator which emits the maximum energy for a determinate temperature and wavelength range[2]. Blackbody radiation spectrum is given by Planck's law:

$$I(\lambda,T)=\frac{C_1}{\lambda^5}\cdot\frac{1}{e^{\frac{C_2}{\lambda T}}-1} \tag{1}$$

where : $C_1 = 2\pi hc^2$
$C_2 = hc/K$
h = Planck's constant
K = Boltzmann's constant

In order to obtain the radiation power of any other material, the concept of surface emissivity, or simply emissivity, which is a material parameter, expresses the efficiency with which an object emits thermal radiation when compared to the theoretically perfect emitter or absorber at the same temperature. Following with the definition of terms, due to the convenience of building up a good glossary, spectral emissivity can be expressed as:

$$\varepsilon(\lambda)=\frac{I_\lambda d\lambda}{I_{\lambda B} d\lambda} \tag{2}$$

where $I_\lambda d\lambda$ is the radiance in the interval $(\lambda,\lambda+d\lambda)$ and $I_{\lambda B}\, d\lambda$ is the radiance of the blackbody in the same wavelength range and at the same temperature. If $\varepsilon(\lambda)$ is constant for all λ, it is referred to as a graybody, and the equation (2) yields $\varepsilon(\lambda)=\varepsilon$. As a last definition, the effective emissivity can be set as the relation between the outcoming radiation of a material and the given radiation following the Planck's law. Normally, effective emissivity is different from surface emissivity due to the geometry of the surface which is the main reason for developing blackbody cavities. In fact, the closest approximation to an ideal blackbody is a cavity with an isothermal interior surface whose aperture has a smaller diameter than the cavity one. Thus, the incoming radiation is absorbed or reflected (in order to be absorbed later) whereas the outcoming radiation is negligible. In subsequent sections, several cavity geometries will be analysed and their effective emissivities will be dealt with.

Although several theoretical studies about the properties of isothermal cavities have been developed [3,4], the geometric shape of real blackbodies is normally an agreement between performance, total size and production costs. There are many practical shapes used to create a blackbody cavity (conical, double cones...), although the most common ones are spherical and cylindrical. Theoretical discussions generally use large spherical bodies with a small viewing opening, because it is conceptually easy to grasp and mathematically simpler to analyze. Nevertheless, the easiness to implement a cylindrical cavity and the effective emissivity reached with it, make it the most used cavity shape.

Flat plates are the least desirable from a emissivity consideration, but are generally the only practical solution when large, uniform areas are required. In those cases, surface emissivity becomes the dominate factor.

If the cavity is assumed to be diffuse, that is, both emission and reflection are independent of direction, and isothermal, the effective emissivity for a cavity can be written as [3]:

$$\varepsilon_{eff_1}=\varepsilon+(1-\varepsilon)\int_{cavity}\frac{\varepsilon_{eff_j}\cos\theta_{1-j}\,d\Omega_{1-j}}{\pi} \tag{3}$$

where ε_{eff1} is the effective emissivity of the cavity (seen from the aperture), $\theta_{1\text{-}j}$ is the angle between surface elements involved in the calculation and ε_{effj} is the effective emissivity of the other element which varies in the integration.
Taking into account the geometry effect over the emissivity, the total radiated power by any material is the product between the effective emissivity and the blackbody radiation at the same temperature, and it is proportional to its absolute temperature to the fourth power as is shown by Stephan-Boltzmann's law:

$$Q = \varepsilon_{eff} \cdot \sigma \cdot T^4 \tag{4}$$

where :

Q = energy radiated

σ = Stephan-Boltzmann constant($5.67 \cdot 10^{-8}$ w/m^{2}K^4)

ε_{eff} = object effective emissivity ($0 \le \varepsilon \le 1$)

T = absolute temperature (kelvin degree)

The capture of this radiated power can be made with optical fiber, owing to its transparency in the infrared spectral range, and it can be measured by an infrared photodetector. The percentage of the ratio of irradiance in a selected spectral range to the total irradiance of the source given by Stephan-Boltzmann's law, is defined as [5]:

$$\eta = \frac{C_1}{C_2^4 \sigma}\left[3! e^{-x_2} \sum_{i=0}^{3} \frac{x_2^i}{i!} - 3! e^{-x_1} \sum_{i=0}^{3} \frac{x_1^i}{i!}\right] \tag{5}$$

where:

$$x_1 = \frac{C_2}{\lambda_1 T}, \quad x_2 = \frac{C_2}{\lambda_2 T} \tag{6}$$

in the $\lambda_1 - \lambda_2$ wavelength range.

Therefore, any object's temperature can be established as a function of its emissivity, the detection spectral range, and the transducer area and it is easy to grasp that it could be used as a pyrometer. Applying the ideas that have been outlined in this section, different sensor systems have been shown by several authors [1,6,7,8].

3. ARQUITECTURES OF THE DEVELOPED TRANSDUCER

The correct design of a blackbody cavity is a complex matter and it demands the use of materials with very specific characteristics, depending on the range of temperatures they are going to work. On the one hand, a material with high thermal conductivity should be used, to get a homogeneous heating of the cavity. On the other hand, the material should have a surface emissivity pretty high (at least over 0.5), to get, considering the effect of the geometry of the cavity, an effective emissivity close to the ideal one.

The material used to implement the blackbody cavity is a mixture of two ceramic matters: alumina and a high-emissivity ceramic paint. The aim is to get a compound which reaches the desired physical properties and has a good bonding strength onto the fiber. The extreme of the fiber has been properly cut and treated with the purpose of having a certain shape: cylindrical or spherical. The mixture is placed onto the fiber extreme in order to create the blackbody cavity. On that point a thermal probe is formed onto the extreme of the fiber by the cavity.

The complete system is composed by several of those described probes creating a multipoint sensor. Each one of those probes, the extreme of its corresponding transmission fiber, has to supply a temperature measurement of a certain section of the steel bar. The probes (and the last piece of fiber) are supported by a high temperature resistant material, which have thermal isolating characteristics (figure 1).

If the cavity is assumed to be diffuse, that is, both emission and reflection are independent of direction, and isothermal, the effective emissivity for a spherical cavity can be written as [3]:

$$\varepsilon_a = \frac{\varepsilon}{1 - (1-\varepsilon)\dfrac{\left(1 + \cos\left(\operatorname{arcsen}\left(\dfrac{r_{app}}{R}\right)\right)\right)}{2}} \tag{7}$$

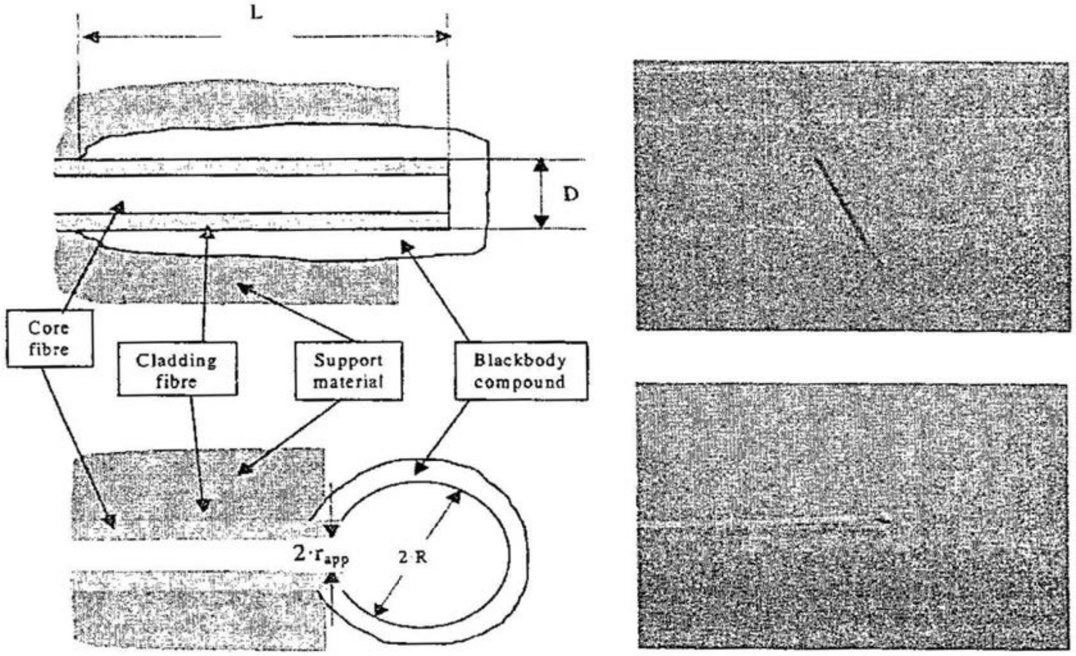

Figure 1. Scheme of the cylindrical and spherical probe.

where ε is the surface emissivity, r_{app} is the radius of the aperture and R is the radius of the sphere. Analogously, the effective emissivity for a cylindrical cavity can be written as [9]:

$$\varepsilon_a = \varepsilon \frac{1 + 4L/D}{1 + \varepsilon(4L/D)} \tag{8}$$

where ε is the effective emissivity, L is the length of the cavity and D is the diameter of the cavity. The figures 2 and 3 show the value of the effective emissivity for both the spherical and the cylindrical cavities.

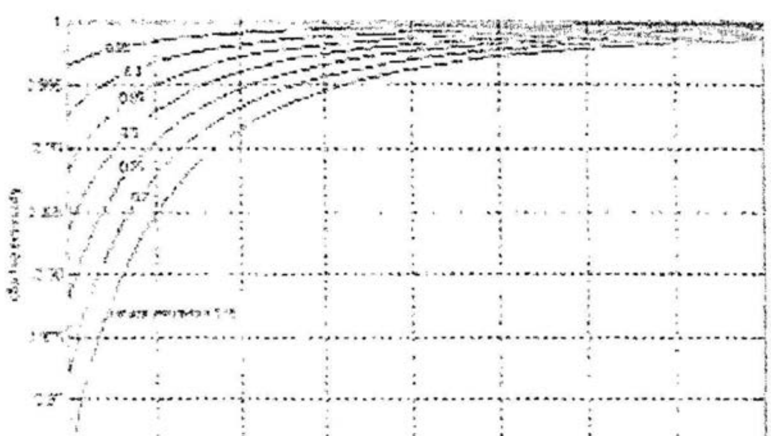

Figure 2. Effective emissivity vs size ratio for a spherical cavity.

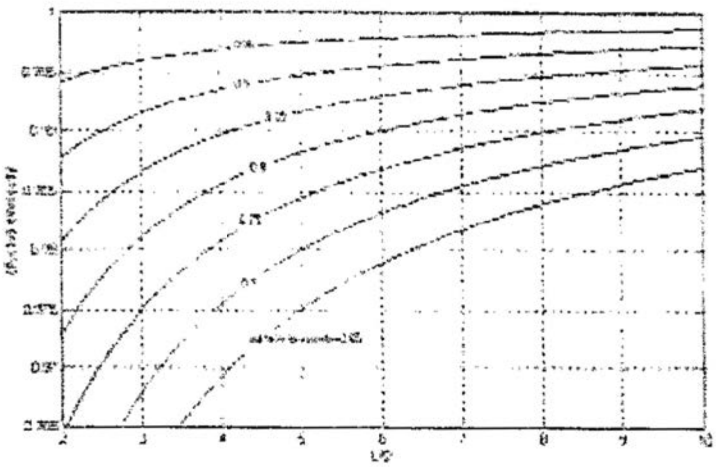

Figure 3. Effective emissivity vs size ratio for a cylindrical cavity.

4. EXPERIMENTAL MEASUREMENT

An experimental setup established to study the response of the different transducers is shown in the figure 4, where a blackbody radiation calibration source irradiates the thermal radiation inside an emittance cone in the transducer's direction. When it receives the heat, it emits an amount of radiation equivalent to the received heat through the optical channel of 100 meters which can be measured by an optical power meter AGILENT 8163 or an optical spectrum analyzer Anritsu MS9701A.

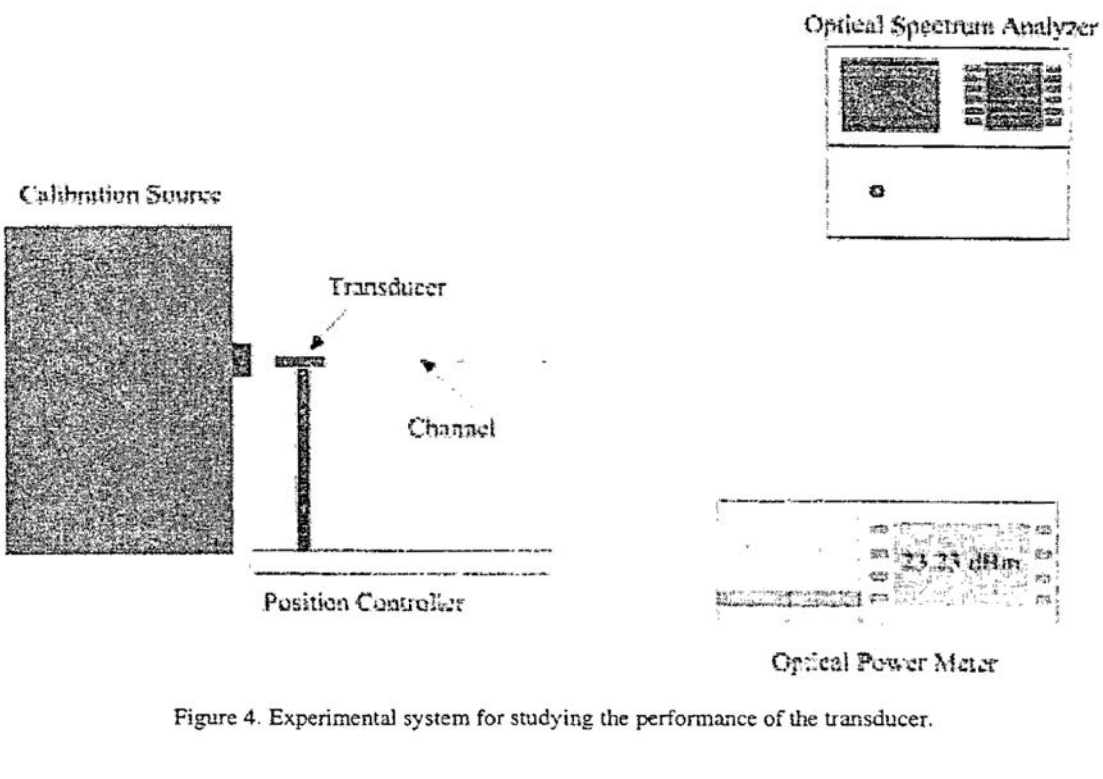

Figure 4. Experimental system for studying the performance of the transducer.

The radiation generated by the transducer is measured by a photodetector, which covers the 1 μm to 1.7 μm wavelength range. The emitted radiance percentage in the aforementioned range is shown in the figure 5 [10]. These values assure a level of power in the photodetector of μW for the worse case (800 °C).

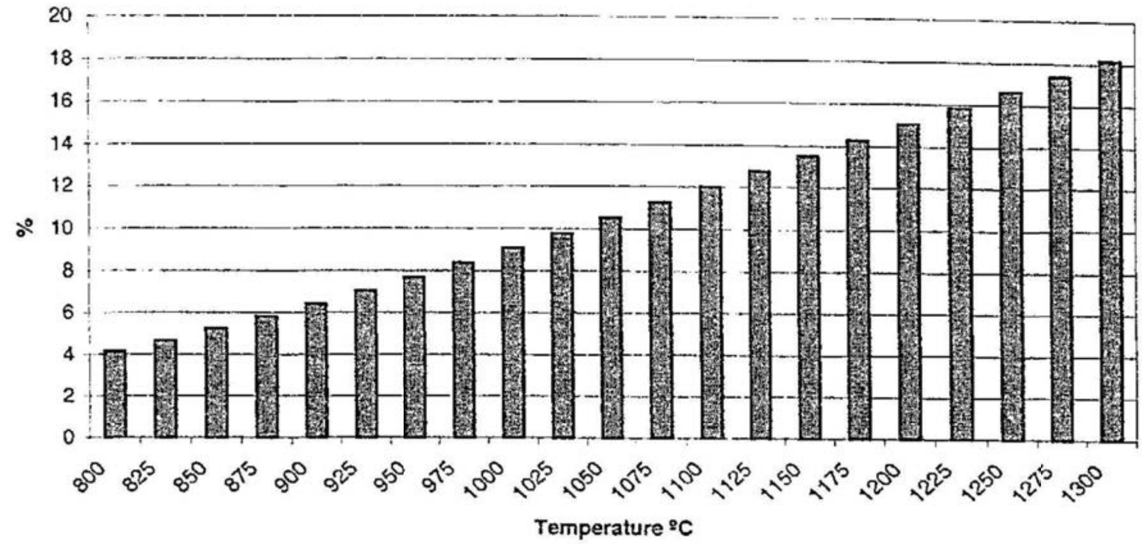

Figure 5. Emitted radiance percentage in 1-1.7 um wavelength range

Two transducer have been made with two different shapes: cylindrical and spherical. In order to make the effective emissivity close to a blackbody one, both the length-diameter ratio(L/D) for a cylindrical cavity or the radius ratio for spherical one has been designed to be 6, which corresponds to both values of effective emissivity 0.997 and 0.99 for spherical and cylindrical cavities, respectively.

The higher effective emissivity of the spherical cavity improve the collected power in the power meter and the measurement of its spectrum permits to use (1) to determinate the temperature value measured by the transducer(See figure 6 and 7).

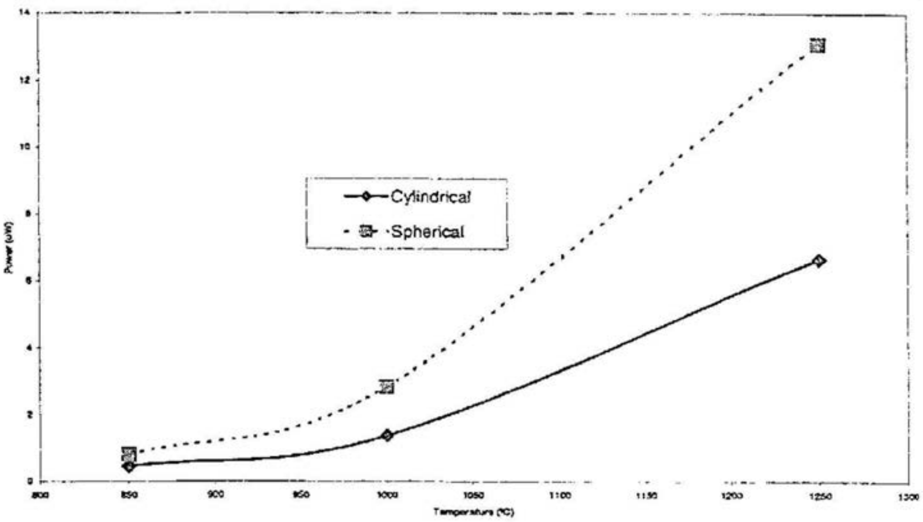

Figure 6. Measured Power from the spherical cavity in comparison with one from cylindrical cavity

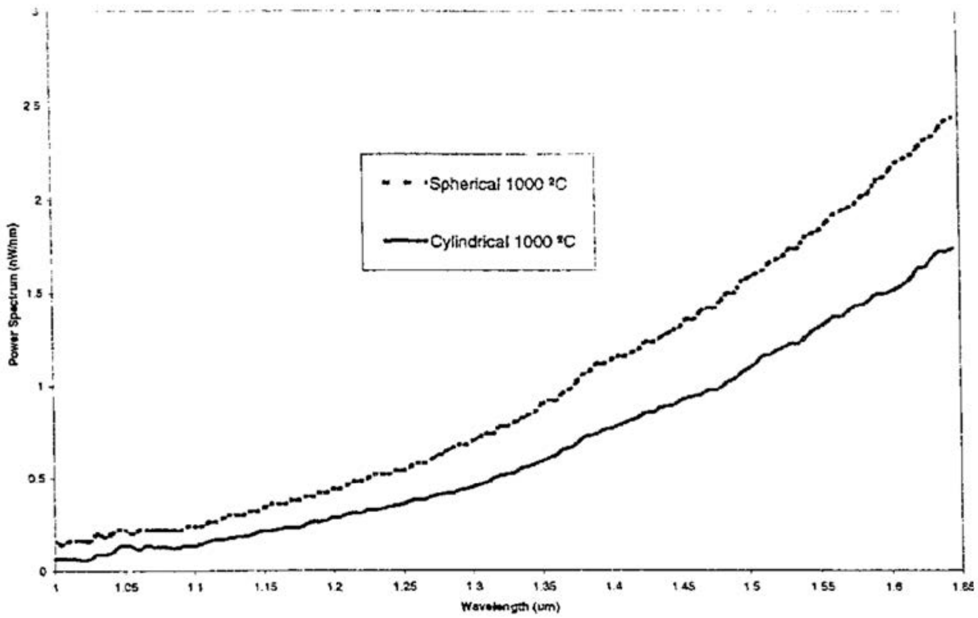

Figure 7. Measured Power Spectrum from the spherical cavity in comparison with one from cylindrical cavity

However, when the measurement is non contact, the temperature of the target is higher than the temperature of the transducer. In those cases the measured temperature is incorrect, so a heat transfer model between two surfaces is used.

As it had been shown(4), the temperature dependence of the energy radiated (fourth power) is much more important than the other two ways of heat transferring (conduction and convection) where the dependence is linear. Especially when the surrounding medium is the air, the coefficients which describe both last mechanisms are low. Thus, the air is a good dissipater although it does not affect to radiation because of its transparency in majority part of the infrared spectral region.

Rejecting conduction and convection, heat transfer between two surfaces can be modelled as an equivalent electrical circuit as is presented in the figure 8 [11,12] :

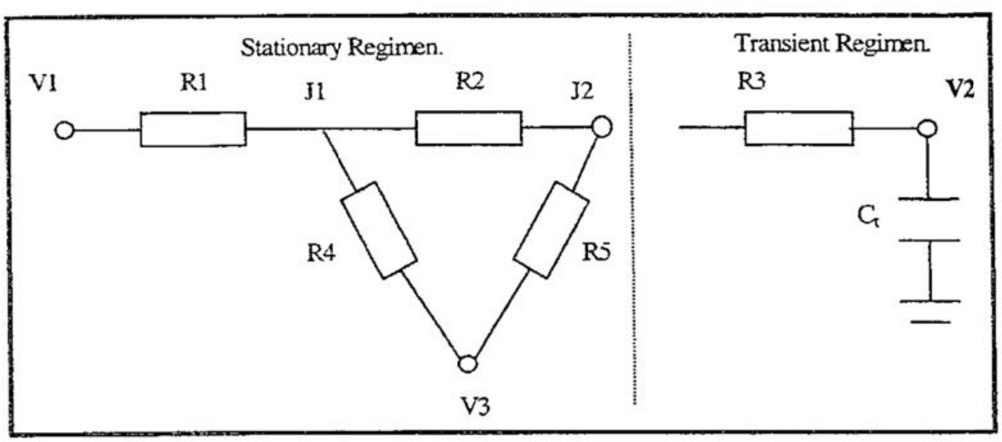

Figure 8. Equivalent electrical model for heat radiation.

To validate the model, the distance between the calibration source and the transducer was changed. The result is shown in the figure 9.

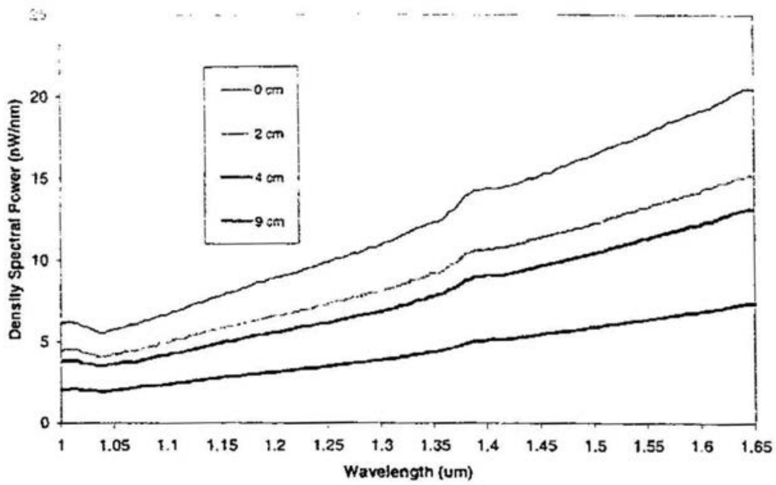

Figure 9. Comparative figure of the measurement of the DSP for different distance between the transducer and the calibration source.

5. CONCLUSIONS

Experimental results show that the spherical cavity-end transducer is better than the cylindrical cavity-end one, because it is closest to the blackbody.

The transducer can be used to measure without contact, applying to the measurement a correction from a heat transfer model. The limit of the distance between the transducer and the target is around 20 cm, but it can be improve if another wavelength range of measurement, where the emitted radiance percentage is higher, is chosen. An optimized channel for the new wavelength range will be necessary at the cost of the system will grow.

Finally, optical communications photodetector could be used in the optoelectronic unit for measuring the blackbody radiation spectrum around 1000°C, which reduces the cost of the system.

6. ACKNOWLEDGEMENTS

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