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A pyrometric technique for gas turbine inlet temperature measurement

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***Abstract* – The paper deals with a non-intrusive pyrometric technique for the real time measurement of the Gas Turbine inlet temperature (TIT), which is a critical parameter influencing both material and coating lifetime of turbines as well as their efficiency. The proposed technique relies on the detection of the radiation emitted in a narrow wavelength band by the CO_2 molecules present in the combustion gas. Preliminary results will be presented relevant to measurements carried out both during laboratory tests and on a full scale test rig capable of reproducing a typical high temperature and high pressure gas turbine environment.**

I. INTRODUCTION

The Turbine Inlet Temperature (TIT) in a Gas Turbine plant is a very important parameter since its knowledge would allow to maximize the overall plant efficiency (i.e. gas temperature could be increased in a controlled way up to the theoretical upper limit) and, at the same time, it could be used to evaluate the residual life of the most critical hot components of the turbine. It should also be emphasized that, because of the very harsh environment actually met inside a Gas Turbine (high temperatures and high pressures), at present there are no available methods capable of providing this measurement on line in operating plants.

To overcome this problem, we have developed an innovative measuring system based on spectroscopic photometric measurements of the radiation emitted (in a selected infrared band) by the CO_2 molecules present in the combustion gases. The experimental apparatus has been designed to provide non-intrusive gas temperature measurements on line and in real time on a plant section (transverse to the gas flow) downstream the combustor. The developed prototype is mechanically robust and thermally resistant so to withstand typical operating conditions of industrial plants. In addition, to simplify installation procedures, it has been designed in such a way it can operate through a single optical access.

In this paper we will present some preliminary measurements carried out both at laboratory level and on a full scale test rig properly designed for reproducing temperatures and pressures typical of a real gas turbine environment.

II. PRINCIPLE OF OPERATION

The measured physical quantity is the grey body spectral irradiance of the hot gas $H(\lambda,T)$, defined by the following equation:

$$H(\lambda,T) = Abs(\lambda,T) \cdot W_B(\lambda,T) \qquad (1)$$

where $Abs(\lambda,T)$ is the grey body absorption and $W_B(\lambda,T)$ is the blackbody spectral irradiance (over 2π solid angle) defined by the well known Planck's law:

$$W_B(\lambda,T) \cdot \Delta\lambda = \frac{1}{\lambda^5} \cdot \frac{C_1}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \cdot \Delta\lambda \ \text{[W/m}^2\text{]} \qquad (2)$$

where $C_1 = 3.74\text{x}10^{-16}$ [J m^2/s], $C_2 = 1.44\text{x}10^{-2}$ [m K] and $\Delta\lambda$ is the selected bandwidth.

As it can be noticed from Eq. 1, if the blackbody behavior can be assumed (i.e. $Abs(\lambda,T) = 1$), the dependence of the measured spectral irradiance $H(\lambda,T)$ on the gas temperature is solely provided by the blackbody irradiance $W_B(\lambda,T)$, so that the gas temperature can easily be derived. To attain a black body condition, measurements have to be carried out in a very narrow spectral band (centered around 4.5 μm) where the carbon dioxide molecules (generated by the combustion process) strongly absorb the IR radiation. Since the measured quantity (the emitted radiation) actually depends on the collection efficiency - which is defined by several instrumental parameters (like e.g. the attenuation of optical components, the collecting angle, the detector response, etc.) that can hardly be theoretically evaluated - it turns out that to get the absolute gas temperature a preliminary calibration of the measuring chain is mandatory.

A calibration procedure has therefore been implemented according to the following steps:

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1. First of all, by means of the experimental apparatus we carry out a sequence of irradiance measurements on a heated solid sample (like e.g. a steel plate or a firebrick) capable of reproducing as close as possible the behavior of a black body at different temperatures. In this way we record the reference signal S_0 generated by a realistic black body in the selected wavelength band $\Delta\lambda_i$ as a function of the increasing temperature T. The experimental curve $S_0 = f(T)$ can therefore be constructed.
2. The second step consists in calculating, by means of the Planck's law, the theoretical irradiance curve $W_0 = f(T)$ emitted in the selected wavelength band $\Delta\lambda_i$ by a black body.
3. Finally, the calibration factor $K = W_0/S_0$ (which actually weakly depends on temperature but, as a preliminary approach, can be averaged over temperatures) can be used to derive the irradiance H_T from the measured signal S_m at any given temperature:

$$H_T(T) = KS_m(T) \qquad [\mathrm{W/m^2}] \quad (3)$$

from which, according to Eq. 2, the absolute gas temperature could be determined.

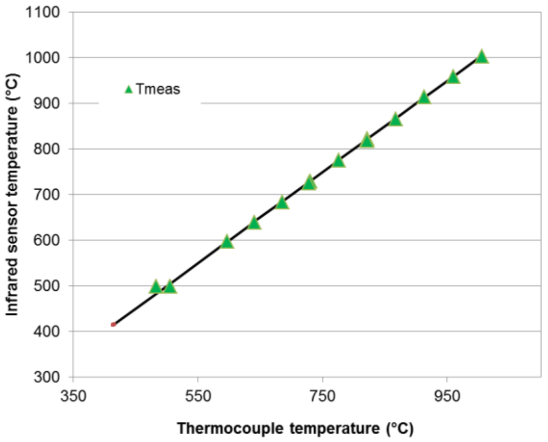

Fig. 1. Comparison between temperature measured by the instrument and temperature measured by a thermocouple in a heated solid sample (a firebrick).

Fig. 1 shows the comparison between the temperature measured by our measuring system after calibration and the temperature measured by a thermocouple embedded in the heated sample (a firebrick) utilized for the calibration procedure. Tests have also been performed with a gas mixture reproducing a typical gas turbine environment. Experimental results will be presented in a following section.

It must be noticed, however, that in case the sample is a fluid instead of a solid (like in our case) both absorption and emission processes occur in the test volume during the heating process so that a balance between these two processes has to be done to evaluate the amount of the emitted radiation. Therefore, to correlate the measured irradiance with the actual temperature distribution in the test region a properly developed emission-absorption model has to be developed to identify the spatial temperature profile that most closely matches the one responsible of the measured irradiance. This model has been derived by dividing the test volume in N identical layers of thickness L/N (where L is the total thickness of the test volume) and by calculating the contribution of each layer to the resulting emitted irradiance according to a balance equation based on the Kirchhhoff and Plank laws [1]. To this purpose each gas layer is supposed to be at a constant temperature T_n whose magnitude is defined by the previously assumed spatial temperature distribution. The theoretical irradiance H emitted by the test volume can therefore be derived by means of the following equation:

$$H = \sum_{n=1}^{N} W_n^B (1 - Tr_n) \cdot Tr_{n-1} \cdot Tr_{n-2} \cdot \ldots \cdot Tr_1 \qquad (4)$$

where: W_n^B is the blackbody irradiance of the layer n provided by the Plank law (Eq. 2), Tr_n is the transmission of the layer n calculated by means of the Hitran database [2] ($Tr_0 = 1$) and

$$(1 - Tr_n) = Abs_n \qquad (5)$$

is the corresponding absorption value (that for a black body at thermal equilibrium is identical to the emission value). Therefore, according to the Kirchhoff law, each element of the sum in (4)

$$W_n^B (1 - Tr_n): \qquad (6)$$

represents the spectral irradiance of the nth layer, that multiplied for the transmission of the adjacent layers provides the actual contribution of this layer to the total measured irradiance.

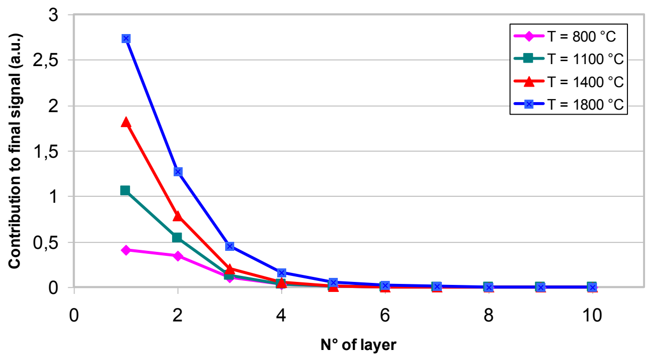

Fig. 2. Contribution of separate layers to the final signal in a 10 layers model in case of a flat temperature profile (L = 48 cm, P = 18 Atm, CO_2 = 4%).

As an example we show in Fig. 2 a simulation relevant to a thick test volume (L = 48 cm) with an almost uniform spatial temperature profile (gas pressure and CO_2 concentration are respectively 18 Bar and 4% in volume). The figure shows the contribution to the final signal of each layer (in a ten layers model) for four different gas temperatures. In this simulation the detector is supposed to be close to the layer number 1. As it can be noticed, only gas layers located close to the detector contribute significantly to the total collected radiation, since the radiation coming from the remaining layers (far from the detector) is totally absorbed by the CO_2 molecules located on the optical path between the layers an the detector.

III. EXPERIMENTAL APPARATUS

The measuring system (schematically shown in Fig. 3) is made by three main units: an optical probe, a detection unit and a data acquisition unit. The optical probe (see Fig. 4) is a metallic pipe (provided with a coupling flange for the installation on the test rig) that supports and screens out of the hot gases the collection optics. It is cooled by water and purged with clean air to prevent the combustion gases from entering into the probe.

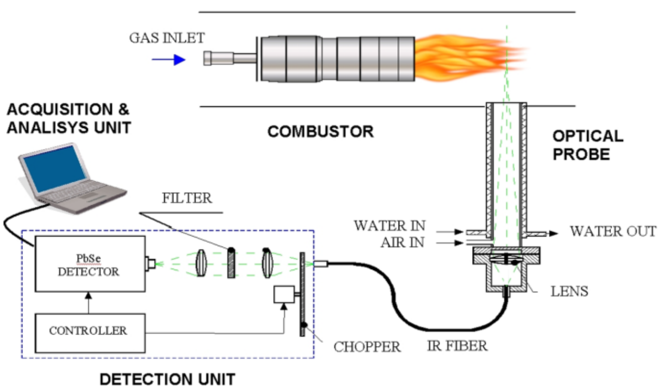

Fig. 3. The experimental apparatus

The detection unit is a separate unit where the measuring process takes place. It is connected to the optical probe via an optical fiber (a Hg halide optical fiber for IR radiation) and contains the detection chain, i.e. the optical sensor (a PbSe photoconductive detector), the interference filter utilized for the selection of the operating bandwidth (centered at around 4.5 µm) and the optical elements required to bring the incoming radiation through the filter to the detector.

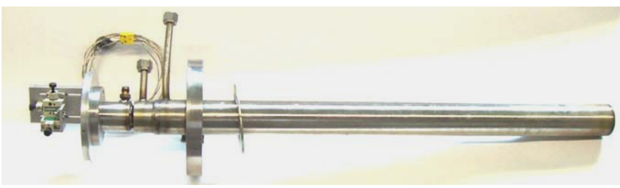

Fig. 4. The optical probe

The IR radiation coming from the hot gases is therefore first collected by a lens and focused onto the input face of the optical fiber connecting the optical probe with the detection unit. Here the radiation emerging from the fiber is first collimated, then filtered by the IR interference filter and finally focused onto the detector. Data acquisition and analysis is carried out by a PC based analysis unit. All the system is controlled via a Labview dedicated software.

IV. EXPERIMENTAL ACTIVITY

Tests have been carried out both at laboratory level and on a full scale test rig.

A. Laboratory tests

The measuring system has been tested by means of a properly developed laboratory setup. To reproduce the operating conditions of a gas turbine combustor (in terms of temperature, pressure and CO_2 concentration), we have manufactured a vertical-axis metallic cell that can be filled with the desired gas mixture and heated up to about 1000 °C (see Fig. 5). To let the inner generated optical radiation escape from the hot region and be revealed, the cell is provided with a properly cooled optical access (a CaF_2 optical window transparent to IR radiation).

The heating process is obtained by inserting the cell into a three sections programmable cylindrical vertical furnace (see Fig. 5). The vertical temperature profile inside the cell is monitored by four thermocouples in contact with the gas. A 45°copper mirror, positioned at the bottom of the cell in correspondence to its optical access, reflects the out coming IR radiation onto the collecting lens of the optical probe.

Fig. 5. The vertical axis metallic cell and the cylindrical vertical furnace utilized for the laboratory tests.

Different tests have been performed on the cell filled with a mixture of 4% CO_2 in N_2 atmosphere at 15 bars during controlled temperature variations of the furnace. It turned out that the measured IR signal exhibits good correlation with the theoretical predictions calculated via the previously described emission-absorption model. As an example we show in Fig. 6 the comparison between the temperature variations measured by our system at a given position inside the test cell (i.e. the local gas temperature derived from the measured spectral irradiance through the emission-absorption model) and the temperature detected by a thermocouple located in the same position. As it can be noticed the agreement between the two curves is quite good.

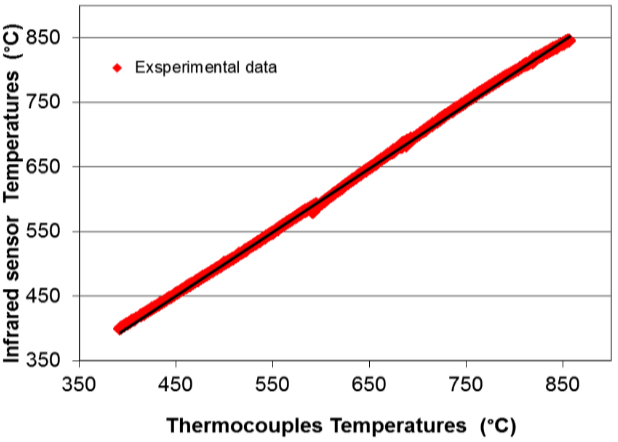

Fig. 6. Measurements carried out on a gas mixture in the test cell: comparison with a thermocouple

B. Experimental activity on a test rig

Measurements on the full scale test rig have been done according to the previously described procedure. We have first calibrated the measuring system (this is done once for ever). Subsequently, according to the foreseen spatial temperature distribution in the test region, we derived the emission-absorption model required to get the correspondence between the measured irradiance and the actual temperature distribution inside the test region. An almost flat temperature profile has been assumed taking into account both the turbulent behaviour of the hot gases downstream the combustor and the existing fluid-dynamic models of the combustion chamber. In Fig. 7 we show the expected signal versus temperature plot relevant to the developed model. By using this curve it is therefore possible to correlate the measured irradiance with the actual temperature distribution in the test region. In particular, from the analysis of the contributions of the single layers to the resultant irradiance (like the one shown in Fig. 2) we get that in this case the maximum contribution to the signal comes from gas layers located at about 10 centimetres from the inner face of the optical probe. As a consequence, we are quite sure that optical emissions coming from the opposite hot wall (that would prevent the correct measurement of the gas temperature) are completely absorbed by the adjacent gas layers and do not contribute to the resulting measured irradiance.

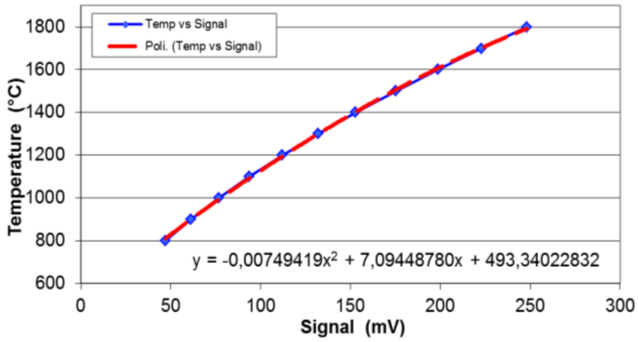

Fig. 7. Calculated signal versus temperature plot

As an example of the experimental results obtained during this test campaign, we show in Fig. 8 the comparison between the temperature detected by the measuring system, the calculated adiabatic temperature and the temperature of the opposite wall (measured with a different optical method). As it can be noticed the agreement between the curves is quite good.

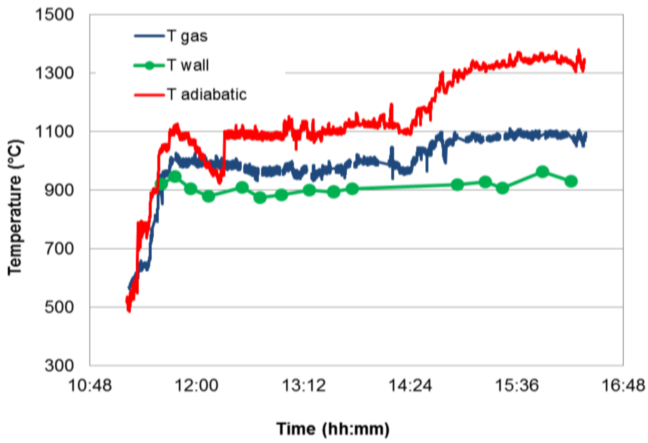

Fig.8. Comparison between the temperature detected by the measuring system and other two reference temperatures.

V. CONCLUSIONS

We presented an innovative optical sensor for the gas Turbine Inlet Temperature monitoring, based on spectroscopic photometric measurements of the Infra Red radiation emitted (in a selected wavelength band) by the CO_2 molecules present in the combustion gases. Main purpose of the sensor is to measure on line and in real time the temperature of the gas flowing in a plant section downstream the combustor. Experimental activity carried out both at laboratory level and on a full scale combustor test rig shows that the absolute temperature of the gas can be derived provided that both a calibration procedure and an emission-absorption model for the analysis of the experimental data are jointly utilized.

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REFERENCES

[1] R.H. Tourin, B. Krakow, “Applicability of infrared emission and absorption spectra to determination of hot gas temperature profiles”, Appl. Opt. vol. 4, pp 237-242, February 1965.

[2] University of South Florida, HITRAN Database. Copyright 1997.

[3] E. Golinelli, S. Musazzi, U. Perini, F. Barberis, “Non intrusive IR sensor for real time measurements of gas turbine inlet temperature”, Proceedings of the AISEM 2013 Conference, Brescia , 5 – 7 February 2013.