Short wavelengths active bichromatic pulsed pyrometer for solids and liquids designed for measurements in harsh environments

Lorris Navello, Jérémy Lebedinsky, Julien-Pierre Offret, Bruno Serio, Tanguy Davin, Yannick Bailly, Philippe Hervé

Short wavelengths active bichromatic pulsed pyrometer for solids and liquids designed for measurements in harsh environments.

L. Navello[a], J. Lebedinsky[b], J.P. Offret[a], B. Serio[a], T.Davin[a], Y.Bailly[c], P.Hervé[a]

[a]Laboratoire Energétique Mécanique Electromagnétisme (LEME), EA 4416, Université Paris Ouest Nanterre La Défense, 50 rue de Sèvres, 92410 Ville d'Avray, France, [b]Lasur Sarl, 119 Rue de Colombes, 92600 Asnières-sur-Seine, [c]Laboratoire FEMTO - UMR 6174, 2 Avenue Jean Moulin, F-90010 Belfort, France.

ABSTRACT

Optical passive methods for temperature measurements such as thermography or optical pyrometry are very interesting because they allow a non-intrusive measurement when the emissivity is known. The knowledge of this coefficient is critical for determining the actual temperature of a surface from the thermal radiation emitted in a wavelength band. The bichromatic pulsed pyrometer allows to overcome the knowledge of this parameter provided that precautions are taken in the choice of the values of wavelengths. When the object to be measured is placed in harsh environments, such passive optical methods are greatly disturbed by the presence of an optically absorbing medium. They are also distorted when the measured objects are located in very hot environments emitting intense disturbing radiation. In this study, we present an active bichromatic radiometric method for measuring the temperature of a surface in harsh environments. The method is based on a localized excitation by a modulated laser source in the infrared range. Detecting the temperature modulation, which is correlated with the excitation, is performed using a lock-in amplifier able to extract the signal embedded in a noise up to a million times superior. Working at short wavelengths (visible range and near infrared range) offers a large dynamic range and minimizes the error due to variations in emissivity with the wavelength. This system collects the radiation emitted by the object at a distance from a few meters up to dozens of meters depending on the configuration of the optical system. Both the principle and the design of the active bichromatic optical surface thermometer are presented and discussed. To demonstrate the method, results obtained on a molten ceramic stream are presented.

Keywords: Bichromatic pulsed pyrometry, short wavelengths, emitted radiation, harsh environment, active and non-intrusive method, signal demodulation.

1. INTRODUCTION

Measurement of high surface temperature in hostile environments remains a particularly complicated problem. The use of contact sensors like standard thermocouple is limited to stationary solid surfaces maintained at temperatures usually below 1500 °C for a type-S Pt/Pt-10%Rh thermocouple for long-term measurement at high temperature[1]. Indeed, over this temperature value, in reactive furnace atmospheres, the alloy of the thermoelectric junction may be not stable. Then, the output response can fluctuate over time due principally to the diffusion of atoms of the alloy. In this kind of configurations engineers prefer to use radiation thermometry because it has some advantages. Indeed, radiation thermometers are better suited in situations where radiation disturbance is high, especially to measure a moving target, a high-speed shock temperature[2] or an object with small thermal capacitance where contactless temperature measurements are necessary. For temperature below 700°C, radiation thermometers working with only one wavelength in the infrared spectral range are usually used. Bichromatic radiation thermometers have some advantages when compared to either monochromatic or total radiation thermometers. The temperature indications of these kinds of sensor are less affected by disturbance such as both optical transmission change of the optical path and variations in the target emissivity[3]. The spectral emissivity is a function of the spectral range, the temperature and the direction of the radiation emitted by the object to be tested.

The purpose of this article is to present an optical method to measure the surface temperature which is suitable for highly hostile environments. The method is based on a photo-thermal excitation of the surface by an intensity modulated infrared laser beam (CO_2). A laser beam pulse induces a small periodic temperature modulation of the surface of the targeted object. The amplitude of the resulting periodic heat flux emitted by the high temperature surface is then measured at two short wavelengths using two lock-in amplifiers. The ratio of these spectral radiation amplitudes depends on the value of the measured object temperature. A calibration on a blackbody is primarily made in order to calibrate the thermometer. An optical system with a well-suited magnification like a telescope with two optical channels was specifically developed to measure the modulated radiation following two wavelengths in the visible and shortwave infrared ranges. Recent studies, focused on the use of shorter wavelengths in the visible range, for various applications in radiometry and thermography, have shown the advantages in working in this short wavelength[4] range even for temperature relatively low (over 400°C for a blackbody).

The proposed bichromatic photo-thermally excited method can eliminate ambient radiation, influence of dust, smoke and soot, often occurring in industrial environments that can disrupt the optical measurement of the local surface temperature. The second section of the study will introduce the implementation of the active bichromatic laser pulsed pyrometry method. The thermometric effect of the sensing method will be presented and discussed in the third section. Principles of usual radiometric thermometers will be presented and a study of the influence of both the temperature and the two working wavelengths on the thermometric effect of our specific pyrometer will be computed and discussed. Experimental set-up and optical design will be then presented in section 4. An example at high temperature presenting a thermogram recorded on a molten ceramic stream in manufacturing industry of glass will be also discussed in section 5. Results have exhibited that the two color active radiation thermometer is well suited for measurements in hostile environment, where surface temperature is above 1600°C and also, in presence of gas absorption phenomena. Indeed, the measured ceramic surface temperature is in good agreement with the temperature prediction value despite the highly radiative disturbance. Finally, section 6 will present the expected prospects in a very hostile environment for an application to the characterization of parietal temperature of a ramjet combustion chamber.

2. PRINCIPLE OF THE ACTIVE BICHROMATIC PYROMETER

The purpose of the method is to determine without any contact the surface temperature of a material submitted to an intense disruptive radiation (like flames, hot walls, etc.) in domains such as the aerospace industry, internal combustion engines, the Tokamak, the chemical reactors (for example reforming) and the glass industry to bound a melt bath. Figure 1 below shows a representation of two kinds of environment for glass and aeronautic industries. In these hostile situations, the radiation coming from disruptive sources and reflected by the surface of the tested material can be much more important than the thermal radiation emitted by the surface itself.

Pyrometric measurements are thus impossible without separating the disruptive radiation fraction from the thermal emission radiated by the measured surface. Furthermore, the emitted radiation can be absorbed by such disruptive radiation (flames, steam or the particles within smokes). This source of error introduces losses of energy in transmitting the radiation from the measured object to the radiation detector and must to be taken into account.

The principle of the photo-thermometry consists in locally exciting the surface of the material with a modulated laser source with a known frequency. In this study, a pulsed infrared CO_2 laser beam which impinges the surface of the target body at 10.6 µm of wavelength was used. The infrared absorption of the laser light increases periodically the local temperature of the excited region (typically a variation of 1 or 2 °C for a 30W CO_2 laser source impinging a ceramic.). The resulting temperature modulation produces a periodic modulation of the radiative emission. The amplitude of this modulation is then measured at two distinct wavelengths in the visible or near infrared range for instance, in order to deduce the actual temperature of the surface. The choice of the wavelengths is crucial to overcome the absorption of the flames, dusts or particles. The ratio of the two monochromatic radiation signals is then extracted by phase-sensitive detection, using two lock-in amplifiers. The ratio is a function of the temperature of the material. Since only the surface temperature is modulated at a specific frequency by the pulsed laser beam, the disruptive radiation flux –not modulated– is then removed.

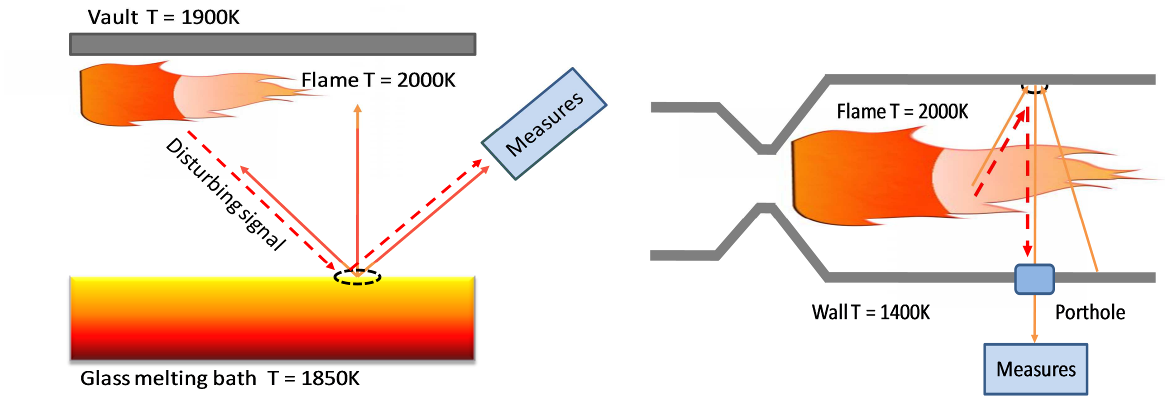

Figure 1: Examples of applications on a glass melting bath (left) and a turbojet engine (right).

3. RADIOMETRIC PYROMETRY METHODS AND SENSITIVITIES COMPARISON

Any body emits an electromagnetic radiation in his surrounding environment. The pyrometry consists in measuring all or part of the emitted radiation and in determining the temperature of the measured surface using thermal radiation laws. One of the main advantages of the pyrometry resides in a transmission of the temperature information of the surface in the form of an electromagnetic wave. The surface is usually imaged using optical radiation-temperature sensing devices which mainly utilize some part of the range 0.3 to 40 µm. Pyrometry thus has the advantage not to disturb the observed thermal phenomenon. Furthermore, the system can be largely deported and does not require an element physically in contact with the measurement point. This aspect is particularly important in a bath of fusion (merger) or a Tokamak where few materials are capable of supporting the environment in the neighborhood of the test point. There are several techniques of pyrometry such as the total radiation pyrometry, monochromatic, bichromatic and photothermal. The three first ones differ from the width of the light spectrum used to realize the measure and their sensibility to the disruptive radiations. The photothermal or impulsive monochromatic active pyrometry is also sensitive to the disturbances but depends on the absorption coefficient of the material too. A schema of a monochromatic active pyrometer is shown in figure 2. In order to be able to compare the selective-band radiation thermometers, the basic operating fundamental relations of usual monochromatic and bichromatic pyrometers and their resulting absolute incertitude ΔT are given and discussed below.

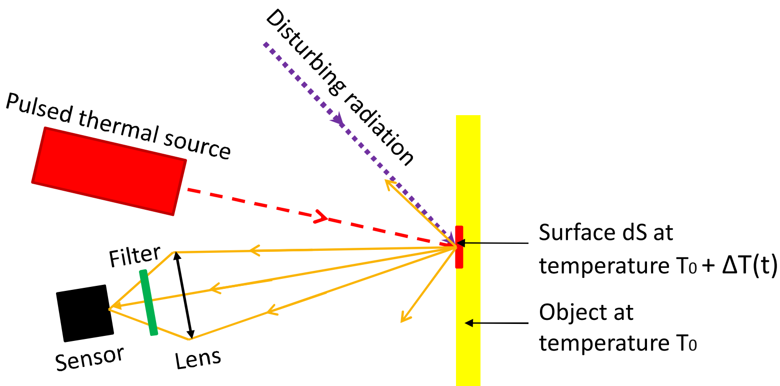

Figure 2: Schematic diagram of pulsed monochromatic pyrometry

3.1 Analytical relation of monochromatic pyrometer

Relation (1) gives an analytic form of a monochromatic radiometer[3, 4]. The temperature given by this kind of sensor is sensitive to the external radiation reflected on the sample and the factor $\varepsilon_\lambda \tau_\lambda$ (ε_λ represents the material's emissivity at wavelength λ and τ_λ represents the smokes transmission at λ. If the target is a blackbody, the factor $\varepsilon_\lambda \tau_\lambda = 1$. In this specific case, if this factor is not equal to unity there will be an error given by the relation (2). This technique does not use a pulsed source like the other "active" techniques. The temperature given by a monochromatic thermometer has the following form:

$$T = \frac{C_2}{\lambda} \times \frac{1}{\ln(\mathrm{cst}) - \ln(S_{\mathrm{continuous}})} \qquad (1)$$

Where $S_{continuous}$ represents the DC radiation signal given by the sensors, λ is the working wavelength and C_2 = 14388 µm.K is the second constant of the Planck’s law. The constant term noted *cst* (relation 1) depends on the absorption and conductivity parameters of the material. In this case, the error can be expressed as follows:

$$\Delta T \approx \frac{\lambda T^2}{C_2} . \ln(\varepsilon_\lambda \tau_\lambda) \qquad (2)$$

The error relation shows that it is better to work at short wavelengths to decrease the error at most, even in the UV range if possible[4]. The drawback is a high sensitivity of the method to the reflection of the ambient radiation on the measured surface as well as the product $\varepsilon_\lambda \tau_\lambda$.

3.2 Analytical relation of bichromatic pyrometer in emission

The classical analytical relation for a bichromatic radiometer is given in a previous study[3]. From this relation we have established the absolute error-for this kind of radiometer, see relation (3). As the monochromatic radiometer, the temperature given by a bichromatic pyrometer is sensitive to the ambient radiation[3]. In this case, the error varies with the values of the two working wavelengths. Relation (3) shows that lowering the working wavelengths will also offer to reduce the absolute error of this kind of method.

$$\Delta T \approx \frac{T^2}{C_2} . \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} . \ln\left(\frac{\varepsilon_1 \tau_1}{\varepsilon_2 \tau_2}\right) \qquad (3)$$

3.3 Bichromatic pyrometry in emission/reflection

Emission and reflection measurements are made at two wavelengths so it is possible to almost eliminate the incertitude due to ε_1 and ε_2 but the method is still sensitive to the ambient radiation[6] and the needed apparatus is complicated. As the three previous methods are dependent on the disturbances and/or the absorption coefficient of the material, a pulsed active method is an interesting method to avoid these problems. Both the analytical relation for this kind of apparatus and its related absolute error are expressed and discussed in the next section.

3.4 Analytical relation of pulsed monochromatic active pyrometer

The temperature given by a pulsed monochromatic active pyrometer is not sensitive to the external radiation reflected on the sample, since for a blackbody the coefficient $\alpha_{\lambda 0} \tau_{\lambda 0} \varepsilon_\lambda \tau_\lambda = 1$ where $\alpha_{\lambda 0}$ represents the absorption of the pulsed thermal source by the aimed surface and the distribution by heat conduction in the material. In the case of a metal the absorption is low and the absorbed flow is mainly removed by the high thermal conductivity of the metal. It is the opposite for the dielectric material which absorbs the pulsed radiation and being thermally insulating does not remove this flow. $\alpha_{\lambda 0}$ is much bigger for a dielectric than a metal. $\tau_{\lambda 0}$ represent the transmission coefficient of the laser beam up to the material[7]. We assume that $\tau_{\lambda 0}$ is close to 1 at the wavelength of the used laser emission (λ_0=10.6 µm). In this case, the temperature is given by the relation (4) below:

$$T = \frac{C_2}{\lambda} \times \frac{1}{\ln(\mathrm{cst'}) - \ln(S_{\mathrm{modulated}})} \qquad (4)$$

$S_{modulated}$ represent the AC signal extracted by the lock-in amplifiers. The constant term noted *cst'* (relation 4) now depends on $\alpha_{\lambda 0}$ and $\tau_{\lambda 0}$.

An expression of the absolute error can be expressed from the previous relation as follows:

$$\Delta T \approx \frac{\lambda T^2}{C_2} . \ln\left(\alpha_{\lambda_0}\tau_{\lambda_0}\varepsilon_\lambda\tau_\lambda\right) \qquad (5)$$

In our case, we have chosen a laser excitation wavelength λ_0 = 10.6 µm where the transmission coefficient $\tau_{\lambda 0}$ is generally very close to 1 because this wavelength is far from the short wavelengths scattering and there is no absorption by atmospheric gases. However, this method (patent n° EP 1984 727A2) is still dependent on the absorption coefficient and thermal conductivity of the material. It can only be used has a benchmark temperature on the same material and under the same experimental conditions, hence the use of the pulsed bichromatic active method.

3.5 Principle and analytical relation of a pulsed bichromatic active pyrometer

Our first publication on this field was published in 2002 and focused on the measurement of temperature of welding[8] and there is no other publication on the subject in the literature to our knowledge. The subject of this previous study was to characterize the dimension of a TIG weld bath (figure 3). Concerning the TIG welding, the radiation emitted by the plasma includes very intense emission lines in the visible range and the reflection of the radiation emitted by the electrode make it impossible to measure the bath temperature with the classical radiometric methods. To illustrate the performance, the obtained thermal image delimiting the size of the bath where the temperature is above 1500°C is presented in figure 3. This study validated the possibility to extract a signal a million times smaller than the noise and the possibility to thermally excite a heat conductive material such as steel. This study was done in our laboratory. The case presented in this paper is different since the studied material has a low heat conductivity. Furthermore the surface targeted is moving and it releases absorbing vapors and smokes at very high temperatures. Moreover the study was carried in harsh industrial conditions. The relation used to compute the measured signal is expressed as follows:

$$L_{(\lambda,\theta,T)} = \alpha_{\lambda 0} \times \tau_{(\lambda)} \times \varepsilon_{(\lambda,\theta,T)} \times \frac{C_1.\lambda^{-5}}{exp\left({C_2}/{\lambda T}\right)-1} + \tau_{(\lambda)} + \rho_{(\lambda,\theta,T)} + L^{external}_{(\lambda,\theta,T)} \qquad (6)$$

Where $L_{(\lambda,\theta,T)}$ is the luminance temperature (or brightness temperature) of the measured object which depends on the wavelength λ, the solid angle θ and the object's surface temperature T (all the indices terms represent the different dependencies). The brightness temperature is the same as the blackbody, which would have the same luminance as the source in the same observing conditions. Planck's law gives the exponential term, it is the blackbody radiation. The unknown are parameters are:

- T the object's surface temperature (in Kelvin);
- $\alpha_{\lambda 0}$ the material's absorption coefficient at the wavelength of the pulsed thermal source;
- $L^{external}$ the disruptive contribution by reflection;
- ε the emissivity;
- τ_λ the transmission coefficient of the flame;
- $\rho_{(\lambda,\theta,T)}$ the reflection coefficient.

C_1 and C_2 are respectively the first and second Planck's constant values (with C_1=1.19104 10^8 W µm^4 m^{-2} sr^{-1} and C_2 = 14388 µm.K), λ is the wavelength expressed in µm and λ_0 represents the wavelength of the pulsed laser source. The periodic thermal impulses on the material induce a temporal variation of the radiative emission of amplitude ΔT. When the continuous component is eliminated, the relation becomes:

$$\Delta L = L_\lambda[T_0 + \Delta T(t)] - L_\lambda(T_0) \qquad (7)$$

Which finally leads to: $$\Delta L_\lambda = cst.\varepsilon_\lambda.\tau_\lambda.\frac{exp\left(\frac{-C_2}{\lambda T}\right)}{T}.\frac{\Delta T}{T} \quad (8)$$

The constant term noted *cst* (equation 7) does not depend on the absorption and conductivity parameters of the material any more, only on the apparatus.

Then, by making the division of the two measures at two different wavelengths we obtain the ratio *R(T)*:

$$R(T) = \frac{\Delta L_1}{\Delta L_2} = cst.\frac{\varepsilon_1\tau_1}{\varepsilon_2\tau_2}.\exp\left\{-\frac{C_2}{T}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\right\} \quad (9)$$

The temperature can now be deduced as a function of *R(T)* in the following form :

$$T = -cst'\frac{C_2}{\ln(R(T))}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right) \quad (10)$$

The sensitivity of the measurement is: $$\frac{dR(T)}{R(T)} = \frac{C_2}{T^2}.\frac{\lambda_1-\lambda_2}{\lambda_1\lambda_2}.dT \quad (11)$$

If dT = 1K (as in the plot presented in figure 4) the ratio *dR/R* is greatly improved if λ_1 and λ_2 are in the short range. To increase the sensitivity, the term $\frac{\lambda_1-\lambda_2}{\lambda_1\lambda_2}$ has to be increased thus to work at short wavelengths. For example, if λ_1 = 0.5 µm and if λ_2 = 0.9 µm then the sensitivity of the pulsed radiometric method is 10% of signal variation for 100°C which is a good result.

The error due to the measurement principle is given by relation (3):

$$\Delta T \approx \frac{T^2}{C_2}.\frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}.\ln\left(\frac{\varepsilon_1\tau_1}{\varepsilon_2\tau_2}\right)$$

The error function is plotted in figure 5. Because λ_1 is close to λ_2 we assume that $\varepsilon_1\tau_1$ is almost equal to $\varepsilon_2\tau_2$ and if $\varepsilon_1\tau_1 \approx \varepsilon_2\tau_2$ we can see through smokes ($\Delta T \approx 0$). If different it must be corrected. This error is second-class compared with both errors established on one hand by the misunderstanding of the emissivity of the material and on the other hand by the reflection of radiations on this material. To decrease the error due to the variation of the emissivity with the wavelength the term $\frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}$ should be decreased at most thus in practice the shortest possible wavelengths should be chosen.

The measuring accuracy depends on the knowledge of the ratio of both emissivities in the chosen wavelengths. This uncertainty can be estimated at 10% and according to relation (11), at approximately 2000 K with λ_1 = 0.5 µm and λ_2 = 0.9 µm we obtain a relative precision $\frac{\Delta T}{T}$ = 2.5% which is satisfying for measuring in a very disrupted environment. Considering the various electronic noises, the sensitivity is about +/- 10 K around 2000 K, that is 0.5%. This sensitivity value allows to control an industrial process in such environments.

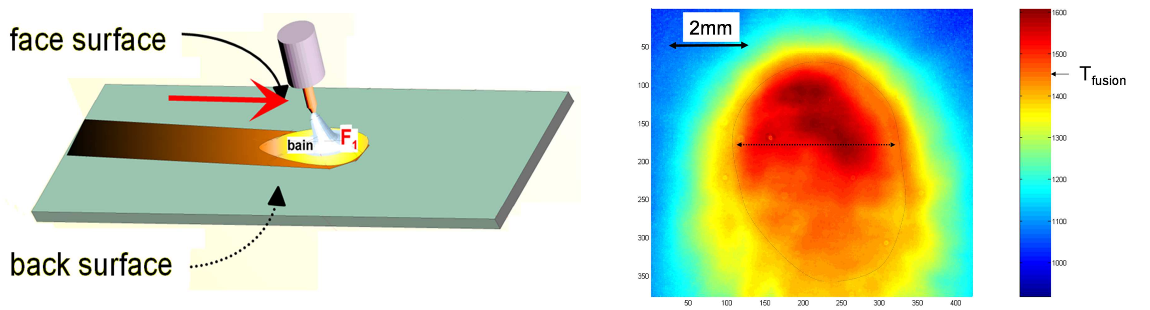

Figure 3: Schematic diagram of the TIG welding (left) and measured temperature field thermal of the bath (right)

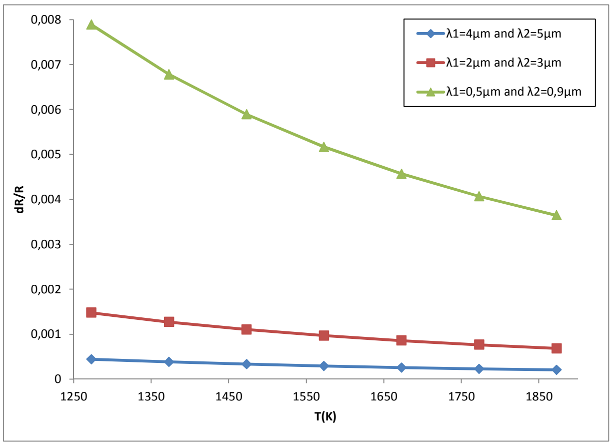

Figure 4: Influence of λ and T on the sensitivity dR/R

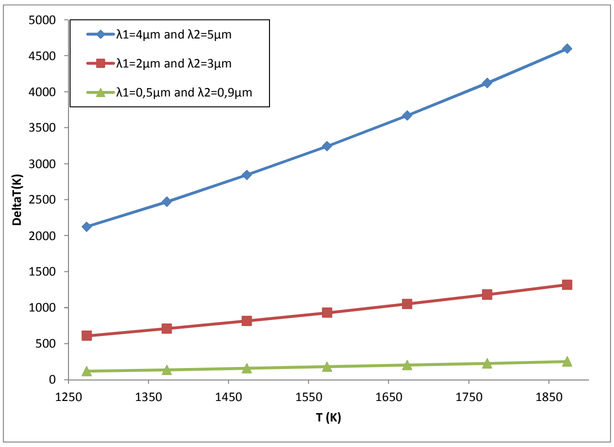

Figure 5: Influence of λ and T on the error of the measurement principle ΔT

4. DESCRIPTION OF THE MEASUREMENT APPARATUS

The apparatus uses a CO_2 laser (30 W of power, class 4) that emits at λ_0 = 10.6 µm, in order to overcome the H_2O absorption in the infrared range. It can be pulsed from a few Hertz up to 5 kHz. The frequency of the pulsation is adapted to the material to have the best measurement amplitude. For example we work at 150Hz to measure a molten ceramic stream. In practice the optical axis has to be the same as the laser beam because the optical apparatus needs to observe in the same direction of the thermal excitation. In order to do this, the laser beam goes through a drilled mirror that reflects the emitted radiation to a second mirror (optional) then into a converging lens. The optical apparatus is composed of a 3' lens (*f*=20cm) and a dichroic beamsplitter that separate the collected radiation as shown in figure 6. The dichroic beamsplitter works like a filter, all the radiation emitted at wavelengths superior to 0.9 µm are transmitted as shown in figure 7. Lock-in amplifiers are used to detect and measure very small AC signals, all the way down to a few nano-volts. Accurate measurements may be made even when the small signal is obscured by noise sources thousands of times larger.
The noise can have various causes, very often electromagnetic disturbances, either the thermal environment in which are made the trials. In our case (remote analysis, a lot of noise), the radiation emitted by walls or flame of a combustion chamber can be 100 - 1000 times larger than the emitted radiation on surface. Lock-in amplifiers use a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase. Noise signals at frequencies other than the reference frequency are rejected and do not affect the measurement.

The final calculations (to obtain the temperature) are also done using the Labview program. A photography of our apparatus is shown in figure 8. The main components are listed below:

- a CO_2 laser source of 25W from ULS, equipped with a neon laser diode for the alignment and pulsed at 150Hz.
- 2 lock-in amplifiers with a 110 dB dynamic range.
- a low frequency generator for the reference of the lock-in amplifiers and the modulation of the laser source.
- a Si amplified sensor from Thorlabs, surface 3.6 x 3.6mm for the acquisition at λ_1 (IR range) and an avalanche photodiode, also from Thorlabs, surface diameter 1mm for the acquisition at λ_2 (visible range).
- a dichroic beamplitter that split the collected radiation at λ_s=0.9µm.
- a 7.5cm diameter lens with *f*=20cm.
- a USB portable DAQ from National Instruments.
- a Labview program for acquisition and calculation purpose.

The apparatus is also equipped for harsh environments with a thermo-isolated enclosing and a built-in cooling system using a Vortex tube (figure 8). Finally, the acquisition of the signals coming from the lock-in amplifiers is done through a USB portable DAQ, which can also provide the phase-sensitive detection and the laser modulation using a Labview program, in case the signals are not too small (mV range). Temperatures are given by the relation 10

Figure 9 presents a calibration curve of the active radiometric apparatus. For temperatures below 1873 K, the results appear linear. This means that a blackbody (ε=1) can be used to calibrate the device with $T(R(T)) = a * R(T) + b$ as shown in figure 9. Indeed, blackbodies above 1873 K are not stable because the source (often made in graphite) is altered by sublimation.

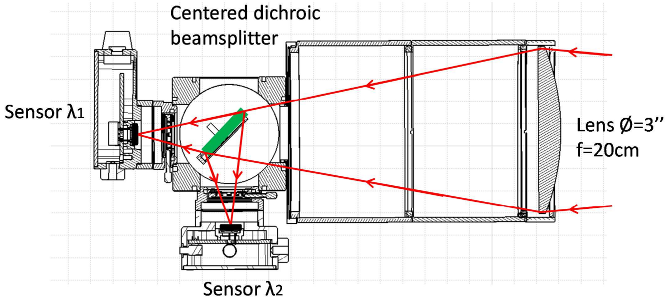

Figure 6: Optical system

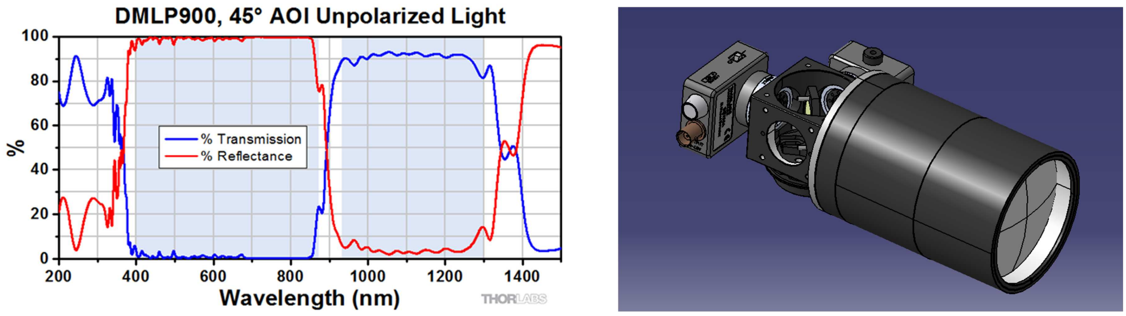

Figure 7: Dichroic beamsplitter characteristics (left) and optical system on Catia® (right)

Figure 8: Photography of the complete apparatus and enclosing

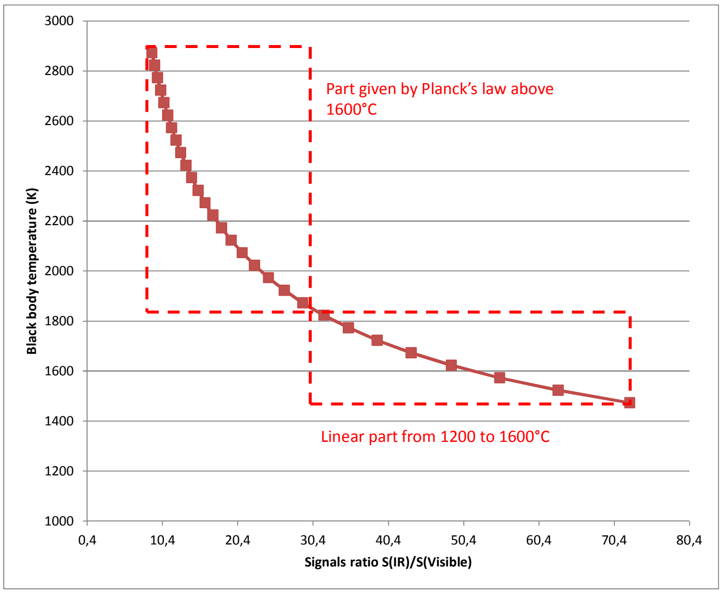

Figure 9: Calibration curve

5. TEMPERATURE OF A MOLTEN CERAMIC STREAM

To demonstrate the performance of our method, the results on a molten ceramic stream are presented below. The aim of the study is to determine the best composition for ceramic bricks used in industrial furnaces (figure 10). These bricks have to resist high temperature above 1600°C. The manufacturing process involves heating the composition up to the melting point, using high power electrodes (from 50 to 500kW) and then cast it into the specified mold. The main issue is to determine the temperature of the casting in order to have both a better understanding and control of the manufacturing process. Figure 11 shows a thermogram obtained for a 500kW cast with a theoretical temperature of 2300°C at a distance of 6 meters. The obtained average temperature is between 2200 and 2300°C except the bump between 25 and 35 seconds. The main problems encountered were a lot of steam and smokes induced by the casting (like instant mold-cooling using water and smokes coming from the furnace during the cast), inducing a lot of absorption. The main disruptive radiation was the radiation coming from the furnace, which was not really a problem since the observed surface was situated outside (see figure 10). But the observed surface was a moving ceramic cast, which explains the "noise" on the thermogram presented in figure 11. The bichromatic results are quite noisy but accurate concerning the theoretical temperature. They also have to be compared to the monochromatic ones that really show the advantage of the pulsed bichromatic method as shown in figure 12. The temperature results with the pulsed monochromatic method are too low, even if when they are recalculated assuming that $\alpha\varepsilon\tau$ = 0.1. This demonstrates the influence of $\alpha\varepsilon\tau$ on the monochromatic method, in this case $\alpha\varepsilon\tau$ must be really low, inferior to 0.1. The influence of smokes can also be noted on the infrared range with the leap observed on T_IR (figure 12) around 50 seconds and also by the fact that the infrared temperature is inferior to the visible temperature.

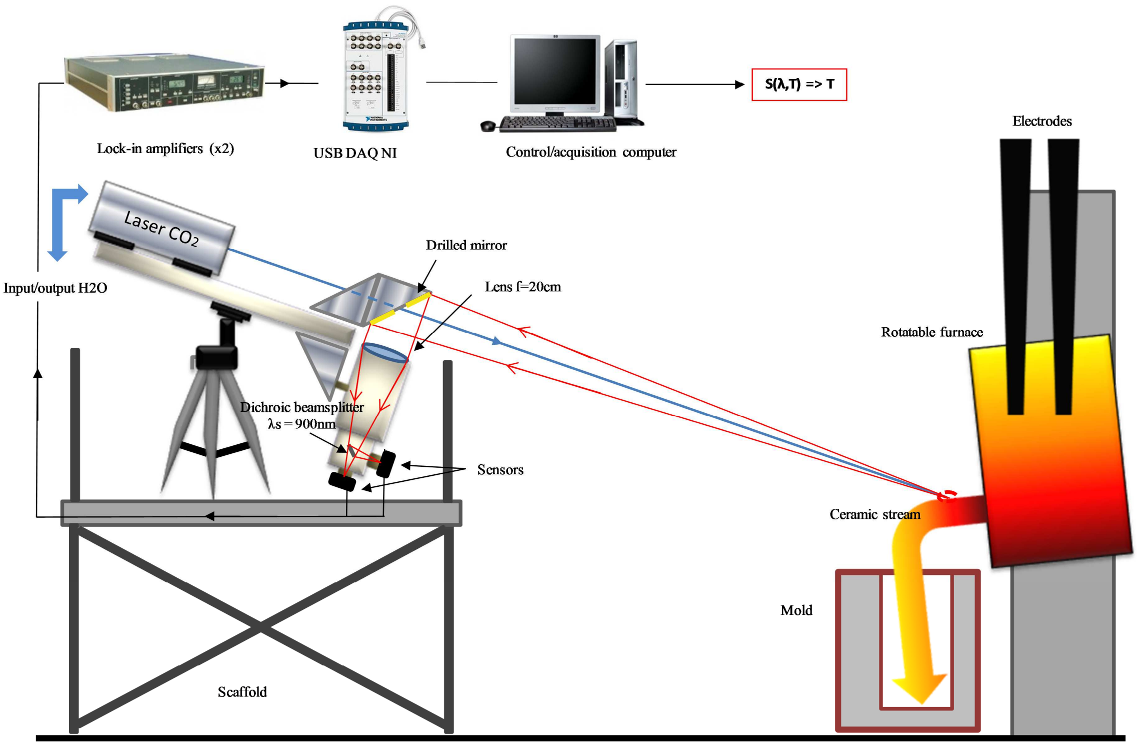

Figure 10: Schematic diagram of the installation

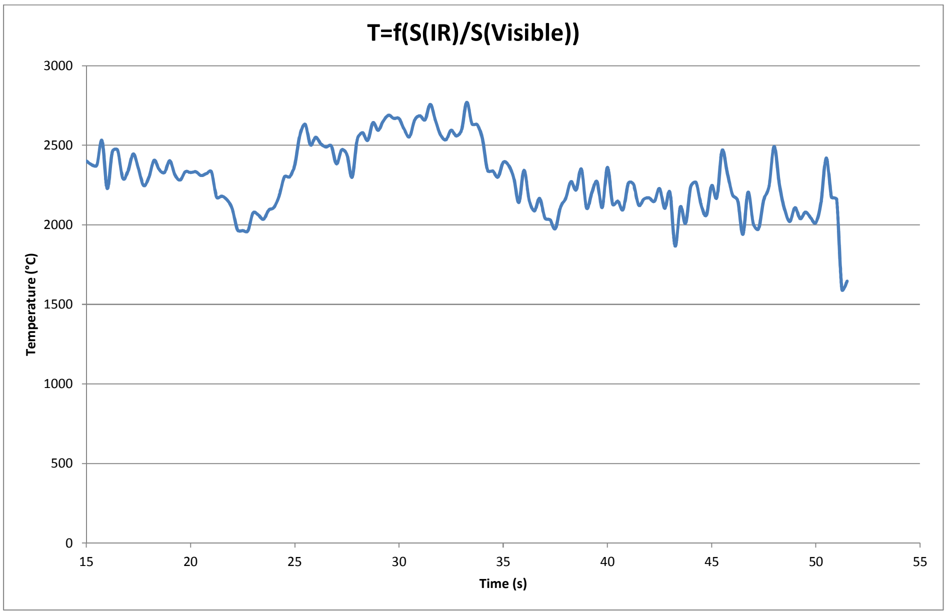

Figure 11: Thermogram of the measured temperature using the pulsed bichromatic pyrometer for a 500kW ceramic cast

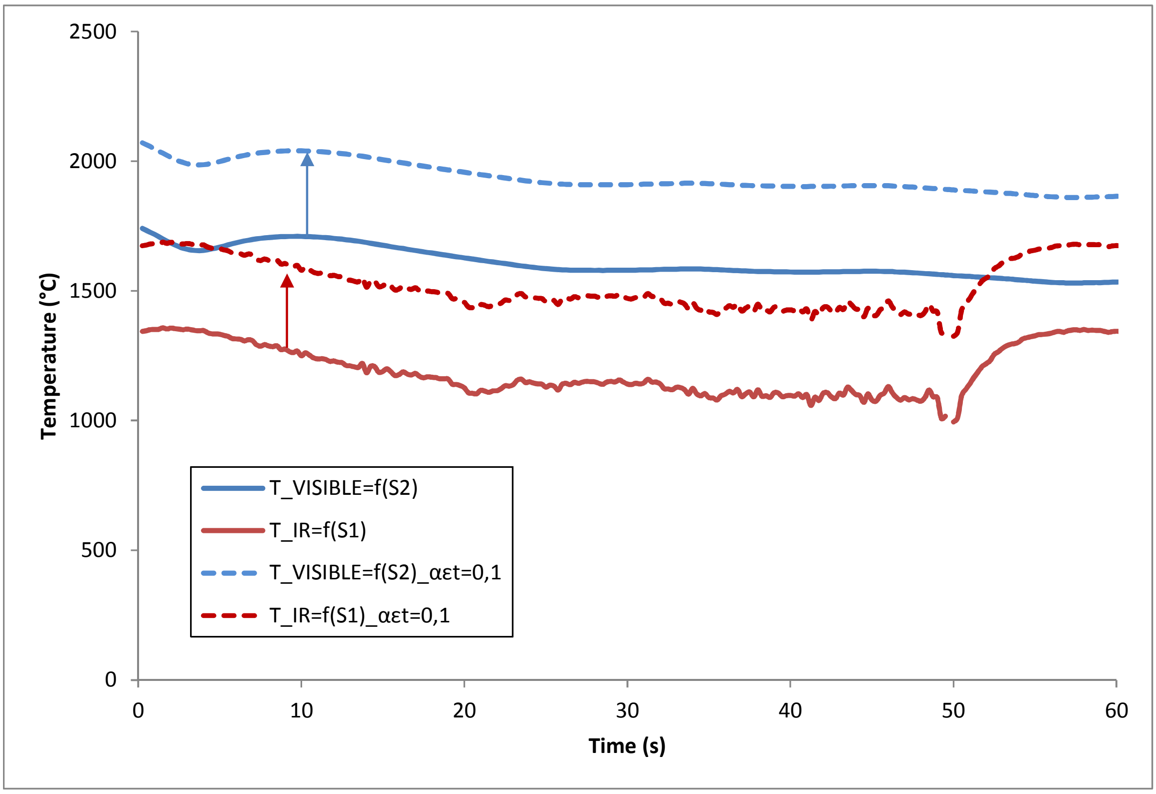

Figure 12: Thermograms of the measured temperature using the pulsed monochromatic pyrometer for a 500kW ceramic cast

6. CONCLUSION

The different results obtained in a high-temperature hostile environment prove that the system is well suited to work with the presence of absorbing phenomena like the ones described above. The pulsed bichromatic pyrometry is capable of overcoming all these drawbacks as long as the 2 short wavelengths are well chosen. Furthermore, the system is able to work on heat conductive materials such as metals, or non-conductive materials (dielectric) like ceramics or glass. For the experiments, a preliminary study of the absorption spectrum should be done before the measurement, which is recommended for the right choice of the wavelengths. With its good sensibility (10% of signal variation for 100°C), its strong dynamic in temperature (from 1000°C up to 2800°C) and its ability to measure signals 1000 times smaller than the ambient radiation, the system is well suited to industrial environments. Finally, the bichromatic method also proved its superiority compared to monochromatic methods mainly because these are disrupted by absorption phenomena (in case of the presence of steam for example) unless the chosen wavelength is in the UV range. The system is currently being used to determine the surface temperature of the outlet chamber of a ramjet or turbojet engine. In this case of a heat conductive material, the main disruptive radiation is the reflection of the flame radiation on the observed surface.

REFERENCES

[1] G. W. Burns, G. F. Strouse, B. W. Mangum, M. C. Croarkin, W. F. Guthrie, P. Marcarino, M. Battuello, H.K. Lee et al. “New reference function for platinum-10% rhodium versus platinum (type S) thermocouples based on the ITS-90. Part I: Experimental procedures”, ITS Measurement and control in science and industry, Vol. 6, Editor James F. Scooley, Part One, AIP publishing, 537 (1992).

[2] Pierre-Louis Héreil and Catherine Mabire, “Temperature Measurement of Tin under Shock Compression”, AIP Conference Proceedings 620, 1235 (2002).

[3] Vinay C. Raj, S. V. Prabhu, “Measurement of surface temperature and emissivity of different materials by two-colour pyrometry”, Rev. Sci. Instrum. 84, 124903 (2013).

[4] P. Hervé, A. Morel, “Thermography improvements using ultraviolet pyrometry”, Proc. of Quantitative Infrared Thermography, 26-31 (1996).

[5] B. Serio, J. J. Hunsinger, and P. Pfeiffer, “Short wavelength thermography: Theoretical and experimental estimation of the optimal working wavelength”, JOURNAL OF APPLIED PHYSICS Vol. 111 (2012).

[6] P.Hervé, J. Cedelle, I. Negreanu, “Infrared technique for simultaneous determination of temperature and emissivity”, Infrared Physics & Technology, 10.1016/j.infrared.2010.09.001 55 (2012).

[7] D Balageas, B Chapuis, G. Deban, F. Passily, “Improvement of the detection of defects by pulse thermography thanks to the TSR approach in the case of a smart composite repair patch”, QIRT JOURNAL, Vol. 7, n°2, 167-168 (2010).

[8] P. Hervé, I. Tkatschenko, “Analyse d'une scène de soudage à arc par thermographie impulsionnelle”, Troisième Colloque Francophone, Méthodes et techniques optiques pour l’industrie, Saint Aubin du MEDOC, 18-22 novembre 2002.