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Brake disc surface temperature measurement using a fiber optic two-color pyrometer

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Abstract

A fiber optic two-color pyrometer was developed for brake disc surface temperature measurement. The two-color pyrometer is composed of a fluoride glass fiber and two HgCdTe detectors equipped with bandwidth filters. The two-color pyrometer allows the measurement of brake disc temperature in the 200-800 °C range with a time resolution above 7 µs. Calibration formula for the signals obtained using a blackbody of known temperature are used to compute the true temperature of a known temperature target. Finally the two-color pyrometer is used to measure the disc surface temperature and the surface emissivity during braking.

Nomenclature

A: Amplification constant, V.W^{-1}.m^{3}.sr
K: error coefficient
L: luminance,W.m-3.sr-1
S: detector signal, V
T: Temperature, K

Greek symbols
Δ: measurement error
Λ: relative signal
ε: emissivity
λ: wavelength, µm
ω: rotation speed, rad.s^{-1}

1. Introduction

During braking, different thermal phenomena appear on the disc surface [1] such as hot spots or hot circles. Panier and al [2] classified the thermal gradients appearance on the disc surface and showed that the understanding of the tribological behaviour of the pad-disc contact depends on the temperature.

In order to determine the disc surface temperature during braking, it is necessary to use a radiometric instrument like IR camera or pyrometer. The observation of the tallest hot spots can be made with commercially available pyrometers or IR camera but certain thermal gradients can not be correctly detected. Indeed some spots have width under 1 mm and duration under 1 ms, furthermore the measure could be made in a high speed rotating disc [3]. On the other hand, radiometric techniques need the knowledge of the brake disc emissivity [4]. Some methods were developped to make emissivity measurement on a brake disc after a succession of brakings [5]. However the evolution of a brake disc emissivity during braking is inexistent to our knowledge in pertinent literature. A conceivable solution is the two-color pyrometry [6,7,8,9]. It enables fast temperature measurements for surfaces with unknown or varying emissivities. In this paper a fiber optic two-color pyrometer for brake disc surface temperature measurement is presented. The two-color pyrometer allows the measurement of brake disc temperature in the 200-800 °C range with a time response of 7 µs.

2. Principle of the method

The theory of two-color pyrometry is given in several references [6,7,8,9]. This method uses an approximation of the Planck's law [7,10,11,12] to determine the luminance:

$$L_\lambda(\lambda,T)=\varepsilon.C_1\lambda^{-5}\exp(-C_2/\lambda T) \quad (1)$$

with C1=3.74´10^{-16} W.m^{2} and C2=1.44´10^{-2} K.m

In practice the measurement signal is a voltage directly proportionnal to the luminance observed by the detectors:

$$S_{\lambda_i}=A_{\lambda_i}.L_{\lambda_i}=A_{\lambda_i}.\varepsilon.C_1\lambda_i^{-5}\exp(-C_2/\lambda_i T) \quad (2)$$

where i Al : Amplification constant of each detector

The two-color pyrometry method measures the infrared luminance at two different wavelengths λ1 and λ2 Assuming that the emissivity remains constant between λ1 and λ2 (grey body behaviour) the voltage ratio from the wavelength outputs S l 1 and S l 2 is used to determine the target temperature T:

$$T = \frac{C_2\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)}{\ln\left(\frac{S_{\lambda_1}}{S_{\lambda_2}} \frac{A_{\lambda_2}}{A_{\lambda_1}} \left(\frac{\lambda_1}{\lambda_2}\right)^5\right)} \quad (3)$$

Then the surface emissivity can be calculated:

$$\varepsilon = \frac{\frac{S_{\lambda_i}}{A_{\lambda_i}}}{C_1 \lambda_i^{-5} \exp\left(-C_2 / \lambda_i T\right)} \quad (4)$$

The temperature uncertainty is given by:

$$\frac{\Delta T}{T} = K\left(\frac{\Delta S_{\lambda_1}}{S_{\lambda_1}} + \frac{\Delta S_{\lambda_2}}{S_{\lambda_2}}\right) \quad (5)$$

where $\Delta S_{\lambda_1} / S_{\lambda_1}$ is the relative uncertainty on the wavelengths outputs and K a factor which depends on λ1, λ2,T, and C2:

$$K = \left|\frac{2T\lambda_1\lambda_2}{\lambda_2 - \lambda_1}\right| \quad (6)$$

Increasing the separation of the wavelengths Δλ=λ1-λ2 reduces the luminance measurement errors but the assumption of the grey body behaviour can be less valid for large value Δλ [7,12]. Therefore the two wavelengths can be determined by studying the relative temperature uncertainty. For T= 1000 °C, the curves of constant value of K are drawn in the space λ1, λ2 (figure 1) . The wavelengths chosen in these study are λ1=2.55 µm and λ2=3.9 µm, leading to K= 1.308. These values are satisfactory to insure a sufficiently small wavelength separation and a reasonable effect on measurement errors.

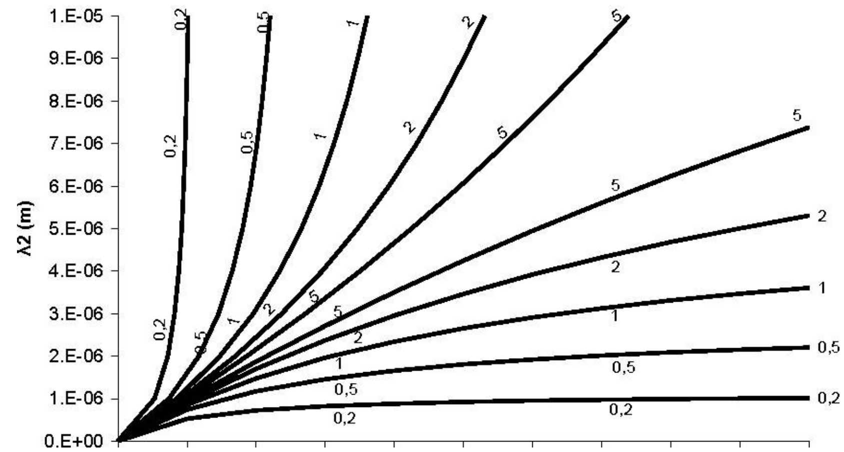

Fig.1. *"Iso-K" curves in the space(λ1,λ2)*

An error coefficient KCR can be defined from the difference between the measured temperature T_1 and the real surface temperature T_2.

$$\frac{T_2 - T_1}{T_1} = \frac{T_2 \ln\left(\frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_2}}\right)}{C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)} = K_{CR} \quad (7)$$

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The coefficient KCR represents the measurement error due to the grey body behaviour assumption. The value of KCR estimated for the two wavelengths previously chosen and taking account the variations of the brake disc materials (steel, cast iron) emissivities given by [13] is within 5%. This error is acceptable for the present application.

3. Experimental device

The two color pyrometer

The two-color pyrometer presented in this study (figure 2) is composed of a fluoride glass fiber and two HgCdTe detectors equipped with bandwidth filters (see table 1). The time response of the HgCdTe detector is under 2 µs. However, the detector signal is amplified by MCT pre amplifier with a bandwith 0-150 kHz and so the time response of the detection system is approximately 7 µs. The fluoride glass fiber has the higher transmittivity (above 0.85 [14] for the spectral range 0.5-4 µm). The optical fiber attenuation is 0.3 dB/m for 4 µm. This fiber allows small measurement spot. For example, if the distance from the fibre to the brake disc is 5 mm, the spot diameter is 2.4 mm.

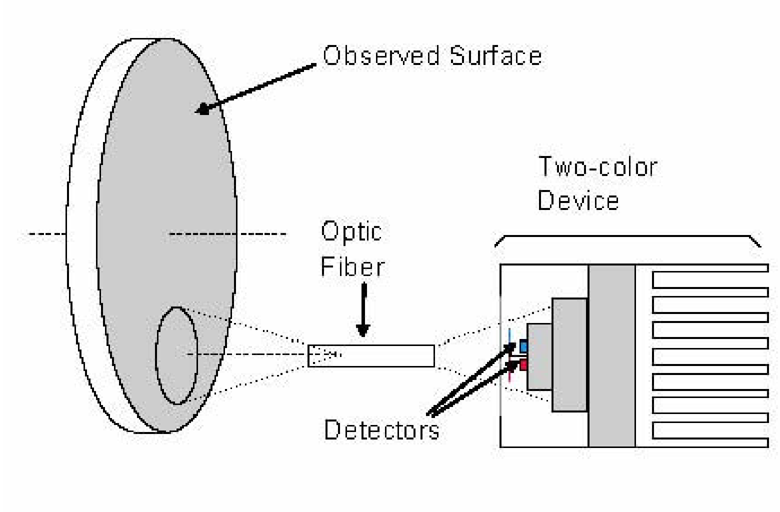

Fig.2. *Experimental device*

Table 1. *Characteristic of the two-color device*

Optical Fiber	Fluoride Glass Spectral range: 0.5-4 µm Attenuation for 4 µm: 0.3 dB/m Length: 1m Transmittivity: 0.85
Detectors	Detector HgCdTe 1mmx1mm Time response: <2µs
IR Filters	Bandwith Filter Filter 1 central wavelength: 2.55 µm±2% Filter 2 central wavelength: 3.9 µm±2% Transmittivity: 0.7

Calibration of the two color pyrometer

The two-color pyrometer was calibrated using a blackbody cavity AGEMA (BB 400-3 emissivity =0.99±0.01). The temperature of the blackbody is varied from 200 to 400°C by step of 20°C. For each temperature, 10 acquisitions are made with the two-color pyrometer. The figure 3 represents the recorded variations for one temperature. The target is alternatively the blackbody cavity (blackbody signal) and the environment at ambient temperature (ambient signal). This figure is representative of the other calibration curves.

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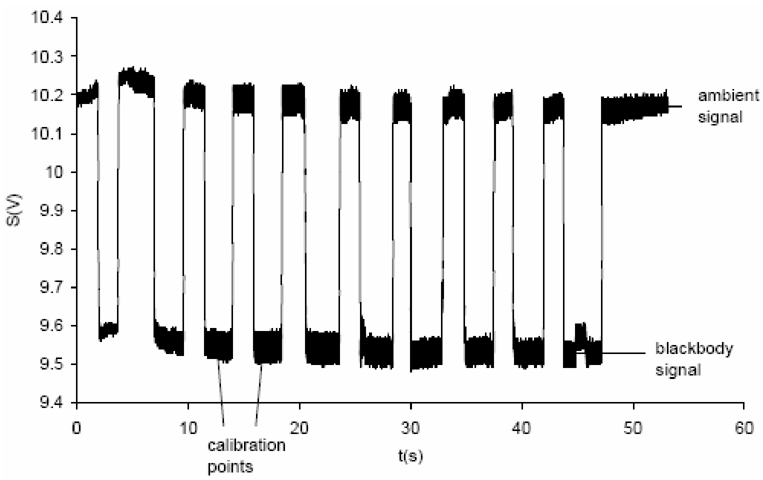

Fig.3. *Example of calibration curve*

From the calibration it appears that the ambient signal is not constant. A recording of the ambient signal was made and the evolution of the ambient signal was confirmed. It was also observed that the difference between the two signals remains constant, so it was decided to use a relative value:

$$\wedge S_{\lambda_i} = S_{\lambda_i,réf} - S_{\lambda_i} \quad (8)$$

For each point of calibration, i réf S l , is the average of the ambient signal, i Sl is the average of the blackbody signal. So for each temperature, thus each luminance, 10 values of i Sl L can be obtained. With all these results, the calibration curves ΛS=f(L) are easily obtained.The figure 4 shows the proportionality between the luminance and the output signal.

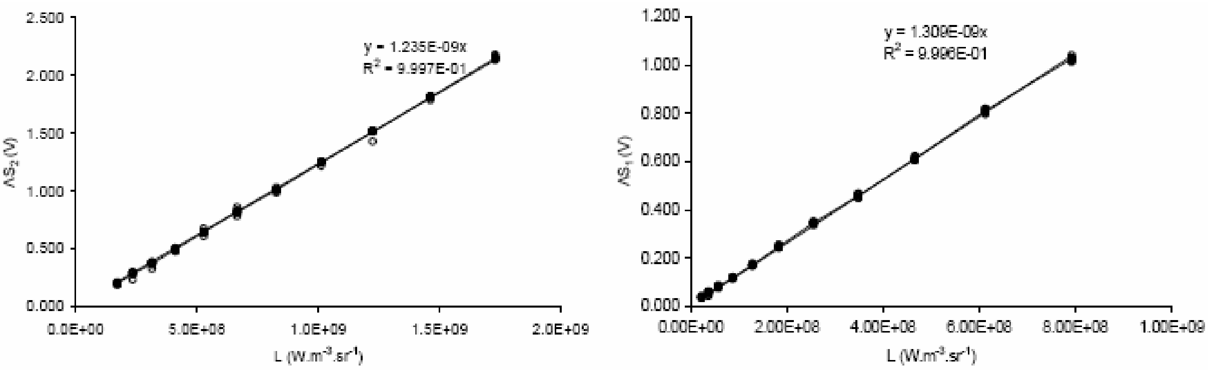

Fig.4. *Calibration Curves ΛS=f(L)*

With a linear interpolation, the two amplification constants are determined:
= A l 1 1.309×10^{-9} $V.W^{-1}.m^{3}.Sr$; = A l 2 $1.235\times10^{-9}$$V.W^{-1}.m^{3}.Sr$

The uncertainties of the signal can be obtained from the calibration results. The relative uncertainty is the ratio of the measurement error over the measured signal $\Lambda S_{\lambda i}$ $\Delta S_{\lambda i}$ is obtained by the calculation of the standard deviation of the measured signal. The relative uncertainty of the signal is determined for each detector. Then the measurement error can be obtained.The curve D T = f (T) is presented in the figure 5. For temperatures higher than 300℃, the estimated measurement error is lower than 10℃.

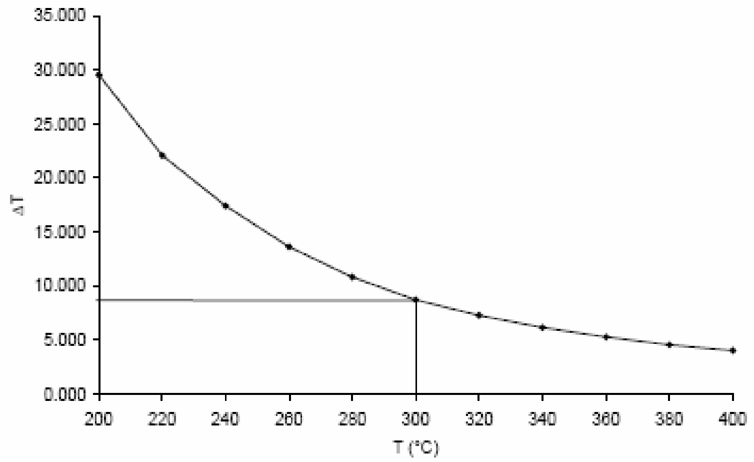

Fig.5. *Uncertainty of temperature ΔT=f(T)*

The uncertainty of the emissivity is given by:

$$\frac{\Delta\varepsilon}{\varepsilon}=\frac{\Delta S_{\lambda_i}}{S_{\lambda_i}}+\frac{C_2}{\lambda_i T}\frac{\Delta T}{T} \qquad (9)$$

Using the same conditions previously given for the temperature, $\Delta\varepsilon/\varepsilon$ remains lower than 0.2 and 0.1 (figure 6) for temperatures respectively higher than 300°C and 360°C.

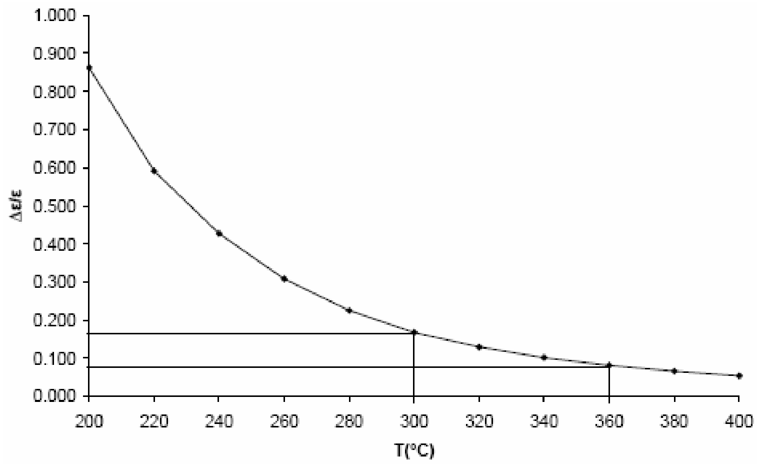

Fig.6. *Relative uncertainty of emissivity*

Experimental validation

To validate the two-color pyrometer, tests were carried out on a disc covered with a black paint. (ε=0.93±0.02). The surface temperature is measured simultaneously by the new two-color pyrometer (T λ1/λ2) and an Impac two-color pyrometer (T bichro). A thermocouple placed at 10 mm inside the disc measures the mass temperature of the disc (TC 10 mm). The disc is heated at a temperature above 400°C, in that case the uncertainty is lower than 5°C. The measurements are presented in figure 7. The temperature obtained with the two pyrometers are almost identical and close to the temperature given by the thermocouple. The higher temperature of the thermocouple is normal taking account the direction of the heat transfer.

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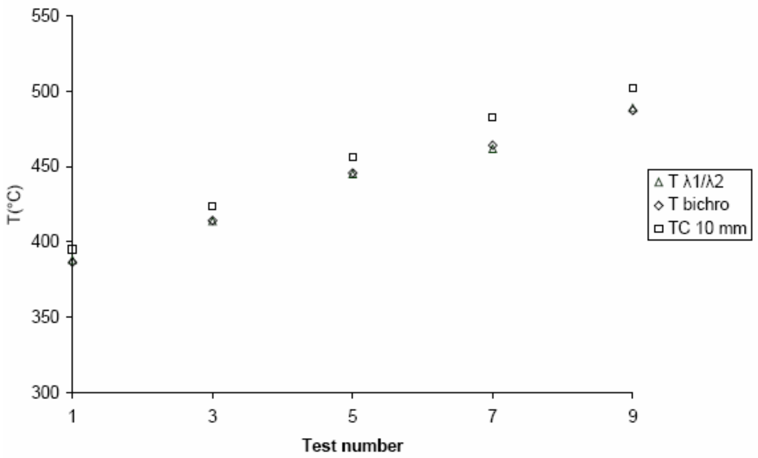

Fig.7. *Disc temperature evolution*

4. Experimental results

Experiments have been performed on a SCHENCK test bench at the C3T (Centre Technologique en Transports Terrestres, Valenciennes).

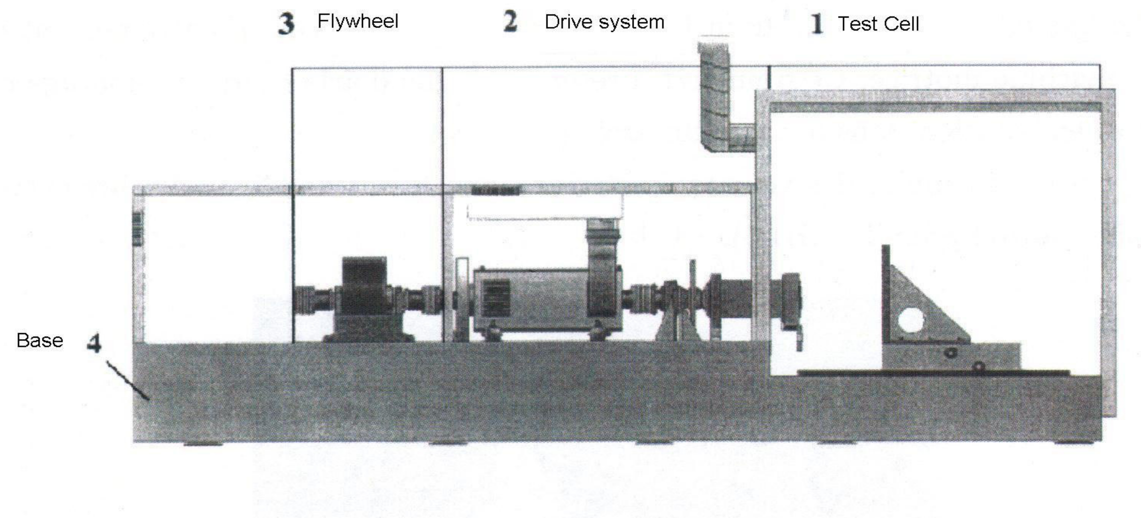

Fig.8. *Representation of the test bench*

This test bench is composed of 4 parts: the test cell, the drive system, flywheels and the base. The test cell is a closed enclosure ensuring a control of the room temperature and allowing a correct ventilation of the disc. The enclosure is equipped with two port-holes for the radiometric measurements. One end of the driving shaft equipped with a revolving collector is in the test cell. The drive system is a DC current machine. The flywheels and the drive system are used to simulate the brake inertia.

The brake system is composed of a 259 mm diameter ventilated disc equipped with 2 K-type thermocouples placed at the friction radius 6 mm under the disc surface and two pads (pad surface:30 cm^2) equipped with 2 K-type thermocouples placed at 5 mm under the contact surface. To control the measurement of the two color pyrometer, the disc surface temperature is also measured by a monochromatic Impac pyrometer. An hold braking result is presented in this article. The conditions of the test are a constant contact pressure of 1.4 bar, a rotational speed of 500 rpm and a braking torque of 192 Nm. The braking sequence is an hold braking during 10 s followed by a cooling as the disc is rotating. The different temperatures are presented in the figure 9:

$T_{\lambda1/\lambda2}$: the temperature measured by the two-color pyrometer

$T_{\lambda1}$ and $T_{\lambda2}$: the monochromatic temperatures measured by each detectors ot the two color pyrometer

T_{pyro}: the temperature measured by the monochromatic pyrometer IMPAC

T_{disque}: mass temperature measured inside the disc by a thermocouple

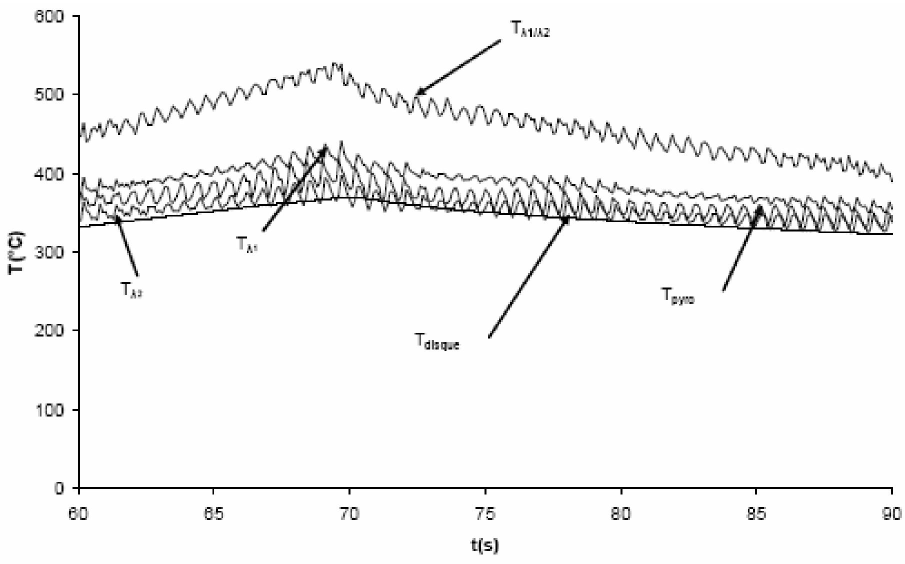

Fig.9. *Brake disc temperature evolution during braking*

The two-color temperature is clearly higher than the other measured temperatures assuming ε=1. For example the difference between $T_{\lambda1/\lambda2}$ and $T_{\lambda1}$ on average 76℃ and the maximum difference is 123℃. This difference is explained by the brake disc emissivity evolution during braking shown in the figure 10:

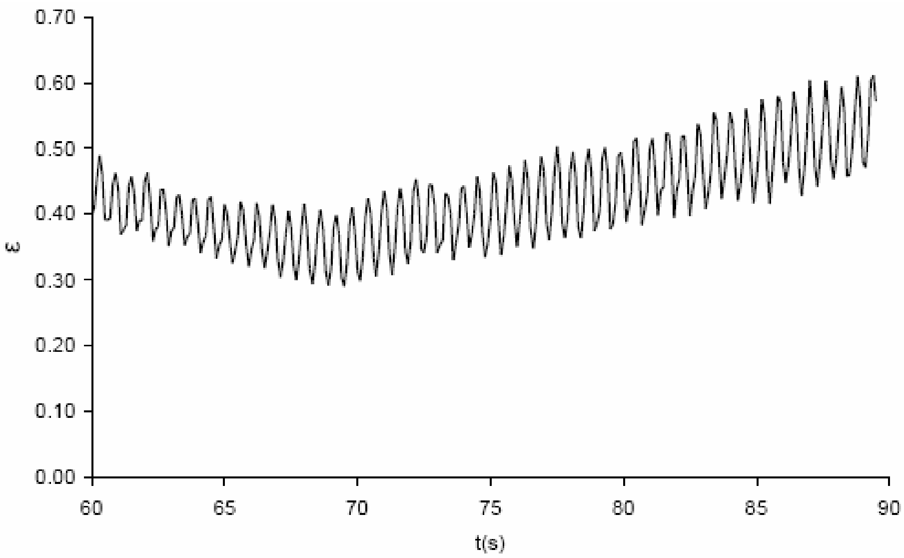

Fig.10. *Brake disc emissivity evolution during braking*

The average emissivity is 0.43. It is coherent with the emissivities measured with others methods [4,13]. The fast oscillations of the emissivity result from the measurement errors and the slowly varying value is the consequences of the evolution of the properties of friction surface.

5. Conclusion

A two-color pyrometer with a low response time was developed that allows the brake disc surface temperature measurement of unknown emissivity. The two-color pyrometer was calibrated using a blackbody cavity. Test were carried out on a known temperature target and good correlation between thermocouple and pyrometer results was obtained. Some experiments were realised on a test bench, which prooved the importance of the emissivity on the measurement of the disc surface temperature. A variation of the emissivity has been observed for an hold braking. Experiments are in preparation to test other braking and other brake material.

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