EXPERIMENTAL DETERMINATION OF EMISSIVITY VARIATION OF A BRAKE DISC BY IMAGE ANALYSIS

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Abstract. *The paper approaches the possibility of determining the temperature repartition of a brake disc by thermography. The repartition was obtained for an intensive brake of a vehicle in real conditions on road. To make a right evaluation of the value and variation of the brake disc material emissivity during the brake, the authors proposed an experimental simulation methodology of thermal flux dynamics during the disc heating. Emissivity variation was made by an analysis of image histograms for brake disc, images taken simultaneously by a thermal and CCD cameras. For better results was used a contact thermometer.*

Keywords: Automotive engineering, disk brake, thermography, image analysis, experimental simulation

1. Introduction

At an intensive brake form high speed, a big quantity of thermal energy is given out by conduction, convection and radiation. Brake disc temperature reaches high values, variable on its surface making possible to appear damages of disc material.

To determine the possible areas with high potential risk is important to know the temperature repartition on the brake disc surface, heat that is store inside its volume (figure 1).

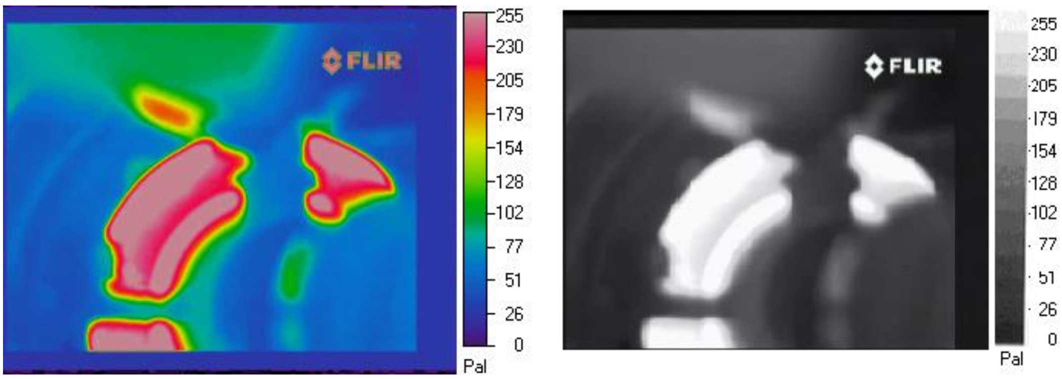

Fig. 1. Temperature distribution (in color units – left, or gray units – right) on brake disc surface.

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The temperature of a moving object can be radiometric determined in a point (with a radiation pyrometer) or planar (with a thermal camera) [1]. With a radiation pyrometer certain thermal gradients cannot be correctly detected, because some spots have width less than 1 mm and duration less than 1 ms, and furthermore, the measure could be made in a high speed rotating disc [2]. On the other hand, radiometric techniques need the knowledge of the brake disc emissivity [3]. The advantage of a planar radiometric image acquisition consists in varied information of temperature distribution in different locations of brake disc (figure 2-3).

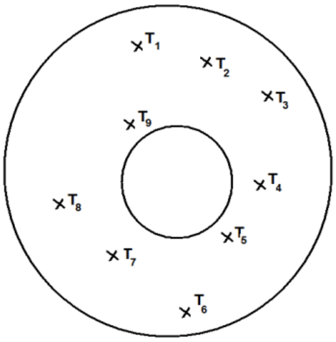


Fig. 2. Repartition exemplification of different temperature areas on the brake disc surfaces at moment during brake.

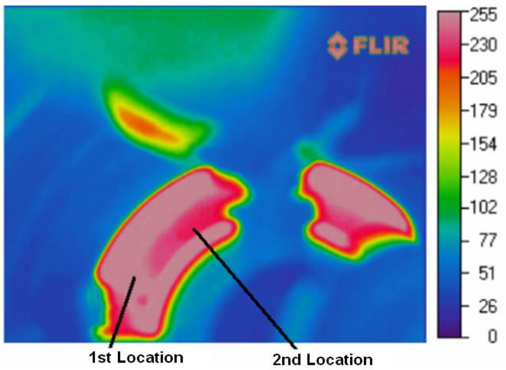


Fig. 3. The thermogram from figure 1 with a emissivity set up to ε=1.

Thermographic cameras are widely used in the fields of material testing and quality control [4], also the thermal images acquisition for different materials heated at the same temperature give different shapes of gray [5].

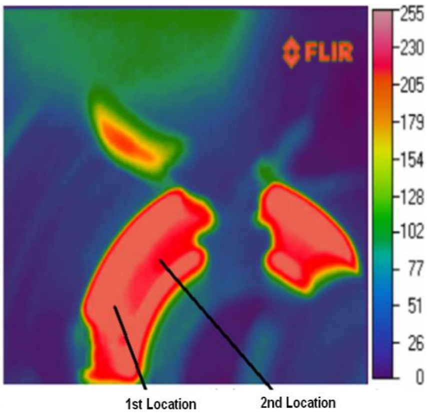


Fig. 4. The thermogram from figure 1 with emissivity set up to other emissivity (ε=0.7).

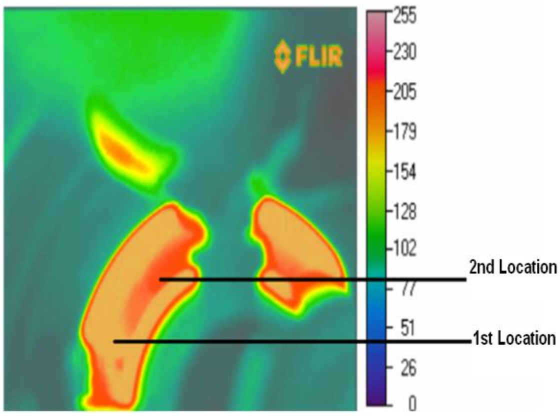


Fig. 5. The thermogram from figure 1 with two values of emissivity, ε =0.6 for the first location and ε =0.5 for the second location.

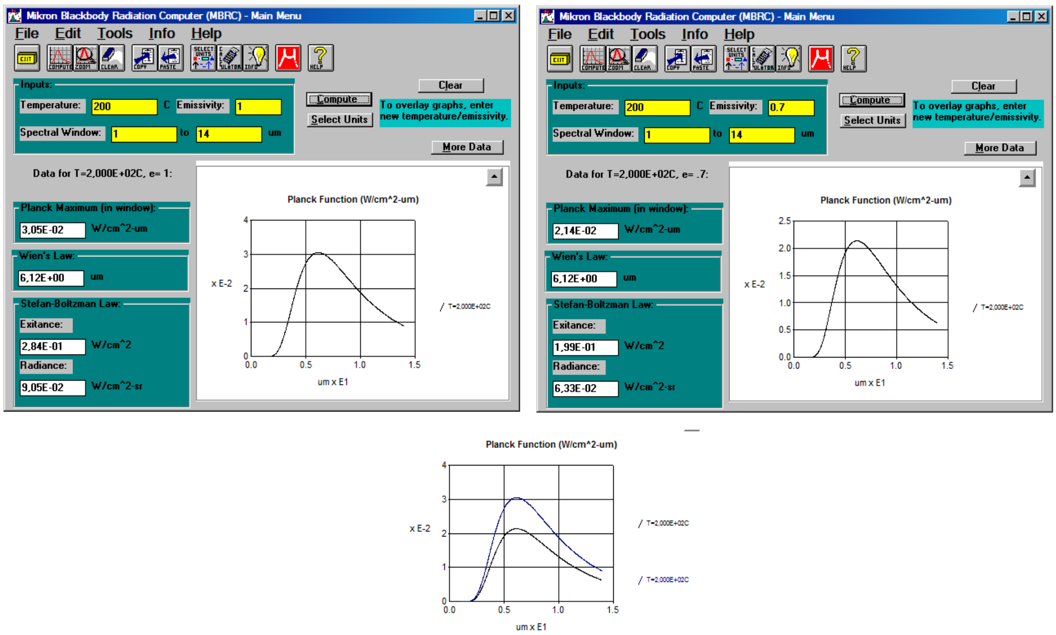


Fig. 6 Planck curve for a black object that could have emissivity ε =1 (up left) and ε =0.7 (up right); in the down part of the figure are compared the two curves

The drawback given by a thermal camera consists in precision of temperature determination unless the emissivity of camera is setup for that moment and that location (figure 4 and figure 5). The emissivity influence can be seen with the quantitative values in figure 6.

The main difficulty encountered in brake disc infrared temperature measurements is the lack of knowledge of the disc surface emissivity, which is not uniform and varies during braking with the local temperature. Indeed, the local emissivity varies with friction due to modifications of surface properties [6]; while the disc heats during the brake, the temperature varies, and the emissivity will permanently varies too. Due to this emissivity vs. temperature variation, the problem seems insolvable. The solution is to determine the permanent variation of emissivity with temperature. Is important to note that the evolution of a brake disc emissivity during braking is practically little studied, to our knowledge, in pertinent literature [1].

Next the paper proposes to present a work methodology that offers enough precision in experimental determination of emissivity variation. The methodology consists in an analyze of images taking in real time in two spectral domains (IR and VIS) with a thermal camera and respectively, with a CCD camera, using as temperature sensor a contact thermometer. The authors considered the suggestion from [7], which refers at some methods that were developed to make emissivity measurement on a disc after a succession of brakes.

2. The work methodology

The principle of proposed method goes from the valid relation for an opaque body for all metals with a great thermal inertia (due to reduced time periods when the brake disc heats different):

$$\rho = 1 - \varepsilon(T) \tag{1}$$

where ρ and ε are the reflectance factor and, respectively, the emissivity factor of brake disc, is considered constant for constant temperatures all over the disc surface.

This relation shows the temperature variation on the disc surface causes an emissivity variation (and implicitly, the reflectance variation) in IR and VIS.

For a constant ambient light, the reflected disc image can be taken by a CCD camera and the thermal radiation is taken by a thermal camera (figure 7).

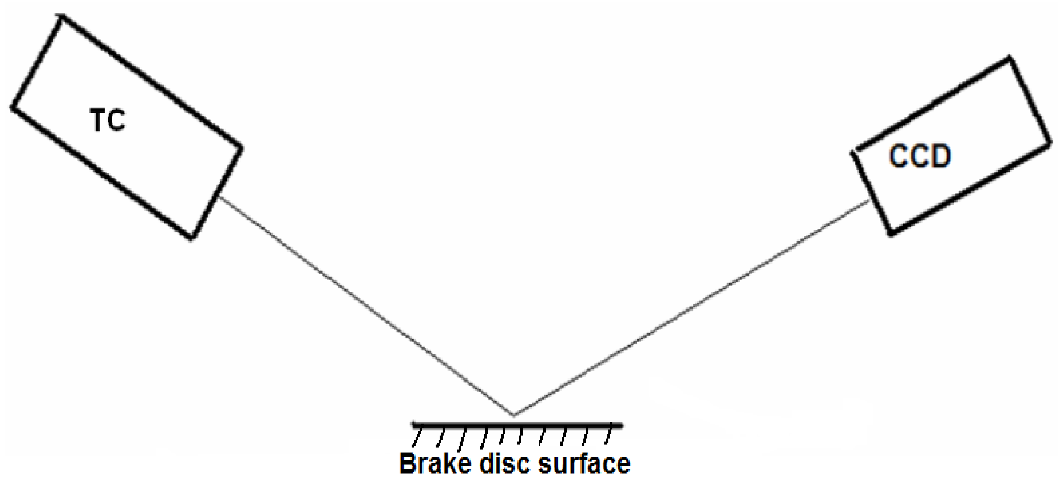


Fig. 7 Positions of thermal and CCD cameras

Due to of easy way of having a high performance CCD camera (with high resolution and contrast transfer) lots of researchers use complementary methods, increasing quality of measurements.

The brake disc thermal image shown in figure 1 is a single sequence from a film recorded and saved on a computer.

This image can be obtained after a heated identical brake disc.

By controlling the modification of thermal energy flux that heats the disc can be obtain any temperature gradient.

This way, with an adequate simulation, for a time period t can be obtain the energy Q_S almost the final energy Q_R at the end of brake process (figure 8).

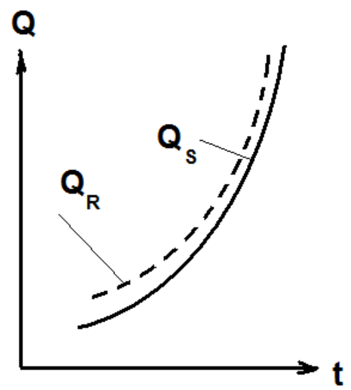


Fig. 8 Differences between dynamic and static disc heating.

Necessity of this method is argued by the fact that CCD cameras offer superior acquisition frequencies than thermal cameras. The reflectance variation can be praised and quantify by analyzing the taken images characteristics, specially using their histograms. Image analysis is a process of searching information from taken image and obtaining histograms from that is the basic of processing technique in the multi spatial range [8]. From practical point of view the histogram provides quantitative information how warm or cold is one IR image. The thermal histogram is an excellent tool to compare two different IR images. It helps also when analyzing the temperature changes on specific object; the thermal dimensional (x, y) model visualizes the flat IR image into as a function of the temperature, where X-axis represent the pixel column of the IR image and Y-axis represents the temperature level [9].

Histograms from thermal images used for temperature diffusion analyzes are used on large scale, specially where a precisely diagnoses is needed [10].

Concordantly with Andonova [9], the calculation of disk brake temperature from the thermal camera output depends on the received radiation power W from this disk of temperature T.

The modern thermal cameras convert the information gathered during the scanning of the infrared spectrum into true color graphical images. Temperature levels are represented by different color palette in accordance to the practical needs. The general concept of thermography, in accordance with the Theory of Three Primary Colors, is to represent the temperature by colorizing the image in the visible spectrum [11].

Thermal imagers usually display images in palettes comprised of 256 discreet color or gray levels. If the disk brake has a temperature difference between 0 °C and 256 °C, each gray or color level would represent 1 degree of temperature difference.

The temperature value T is distributed for each unique color in the palette as follows [9]:

$$T = T_{min} + \sum_{0}^{C_T - 1} \frac{abs(T_{max}, T_{min})}{C_T} \quad (2)$$

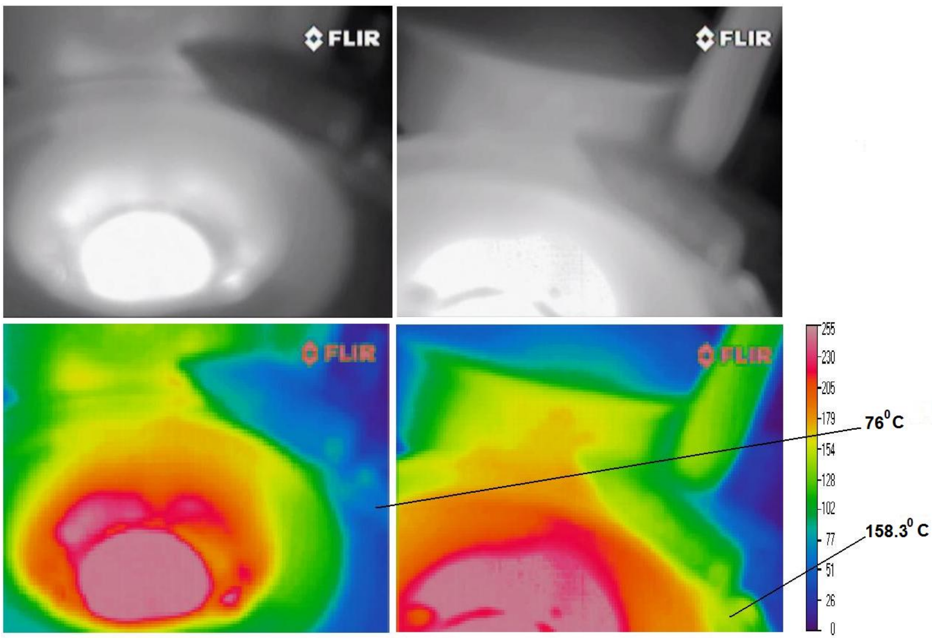
where T_{min} and T_{max} are the minimal and maximal temperature levels detected by the thermal camera, $C_T = C - C_G$, C is the count of all unique colors from the palette, C_G is the count of the garbage colors. In the same study direction, the authors started from Plank`s law:

$$E_\lambda(T) = \frac{C_1}{\lambda^5}\left(e^{C_2/\lambda T} - 1\right)^{-1} \quad (3)$$

where $C_1 = 0.59552 \times 10^{-16}$ [Wm^2], $C_2 = 1.438769 \times 10{-}2$ [mK], and E (λ, T), λ is the radiance at a given wavelength λ and a given absolute temperature T [12]. This law shows the existence of a proportion between images shining parts of a CCD camera that takes picture of a radiation source with the E energy:

$$\frac{E_{\lambda 1}}{E_{\lambda 2}} = A \frac{L_{\lambda 1}(T)}{L_{\lambda 2}(T)} \quad (4)$$

where $L_{\lambda 1}$(T), $L_{\lambda 2}$(T) are the color intensity under the wavelength λ_1, λ_2 and A is a correction coefficient.



a) Temperature at 1:26 minutes; b) Temperature at 5:02 minute

Fig. 9. Thermal images (gray and pseudocolor) of a brake disc heated with an external thermal source at different time intervals.

The experiment stages are as follows: in real time is taking two films with a thermal camera and a CCD camera, from these films are used images at known time intervals. The next step is to simulate the thermal regime for different temperature gradients using external thermal source.

The disc used has the same geometrical and material proprieties as the same from the motor vehicle (figure 9).

The images from figure 10 show a part of disc with low reflectance (a), a part of disc with high reflectance (b) and in (c) figure is exposed histograms of the images. Images are taken simultaneous with thermal and CCD cameras (see figure 7).

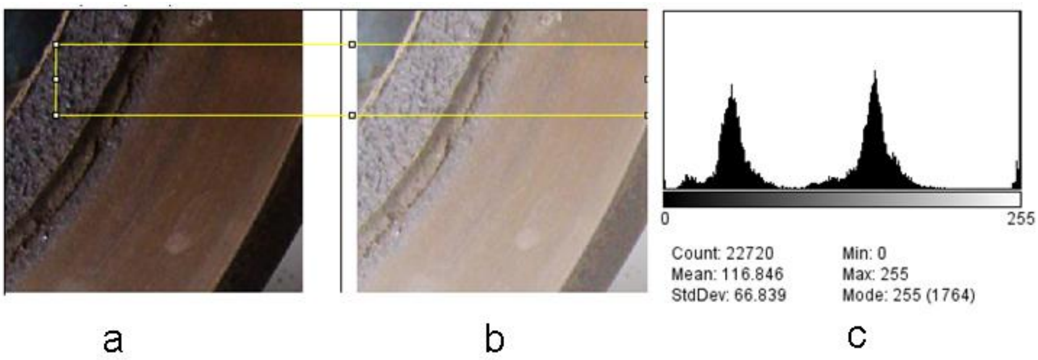


Fig. 10. Histograms obtained for images taken by a CCD camera.

Real temperature and the time are recorded with a contact thermometer and a chronometer. The analyses consists of selection in every image, of interest areas which can contains pixels of high brightness (possible as no saturated), as pixels from immediate proximity. Approximately equal areas are selected to avoid influences over the temperature (figure 11-15).

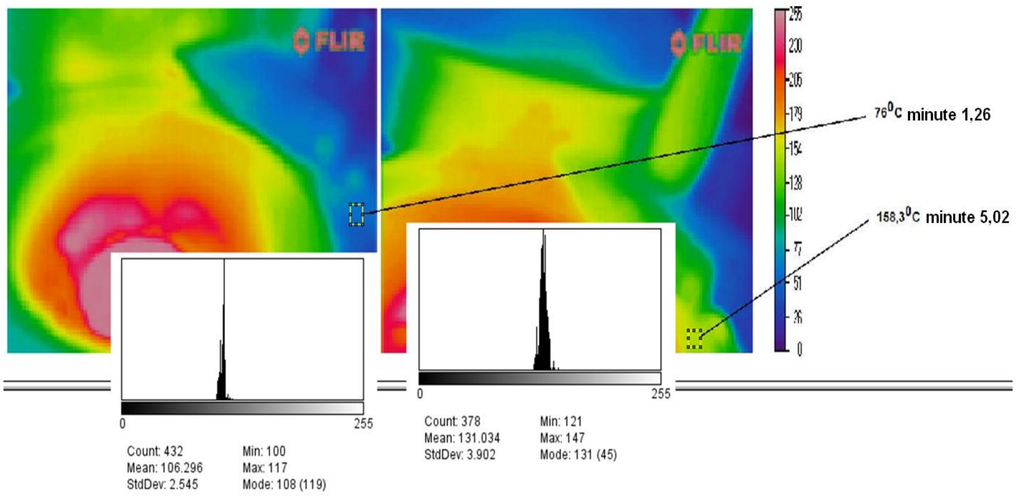


Fig. 11. Emissivity histograms of taken thermal images.

Fig. 12. Temperature indicated by contact thermometer (196.5 °C) and the selected area and for histograms.

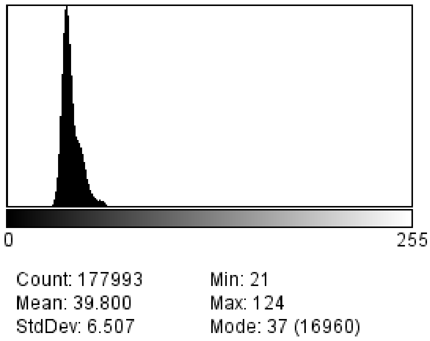


Fig. 13 The histogram of a element heated at temperature of T=196.5 °C.

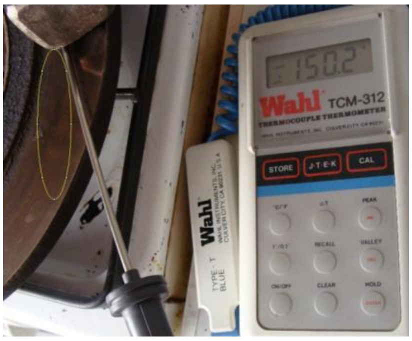


Fig. 14 Temperature indicated by contact thermometer (150.2 °C) and selected area for histograms.

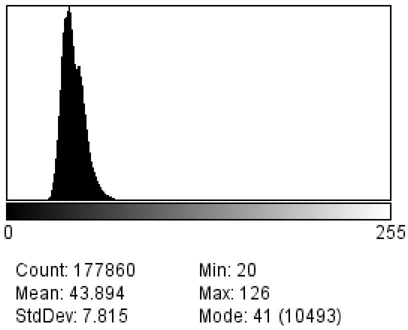


Fig. 15 The histogram of a element heated at temperature of T=150.2 °C.

It's expected to exist a linear shape of the exit signal from the photons impact with every CCD camera's pixel, thus to be a relation between the luminance L and every gray level under the form [13]:

$$N_g = m \cdot L + N_{g0} \tag{5}$$

where N_{g0} – the noise level and m – the spot.

If there are two different values of emissivity on thermal camera used for measures, the thermograms will have different displayed temperature values. So, this is the reason of necessity of knowing the value or the variation of emissivity.

There were used devices with next characteristics: thermal camera with 19 mm object lens, a spectral domain of 8-12 μm, 320×240 pixels resolution, CCD camera with a resolution of 3264×2448 pixels, electronic contact thermometer with the measure domain of 0…1800 °C and an error of ±2%, Dacia Logan non vented brake disc, Software ImagePro for calibration and realization of images, Software MikroView 2.9 for conversion of image from gray to pseudo color.

2. Results and interpretation

The histograms characteristics results were presented in table 1 and 2 and in figure 16 and 17.

Table 1

Emissivity and reflectance variation with temperature for oxidized steel

Temperature [^{0}C]	100	499	1199
Oxidized steel emissivity ε	0.74	0.84	0.89
Oxidized steel reflectance factor ρ	0.26	0.16	0.11
Reflectance factor ratio ρ_i/ρ_0 at 100^{0}C	1	1.625	2.36

If a black pixel has a color index value zero and for a white pixel is a index value of 255, results that for a medium value higher in histograms means a higher image reflectance factor, so a smaller emissivity factor. A disc element histogram, heated at 196.5 °C has the average 39.8 and the element histogram for a disc heated at 150.2 °C has the average 43.89. So, we can write: $L(T = 150.2\ °C) = 43.89 > L(T = 196.5\ °C) = 39.8$ and, consequently, $\varepsilon(T = 150.2\ °C) < \varepsilon(T = 196.5\ °C)$, so it's like the data from table 1.

From here the results are presented in table 2.

Table 2

Reflectance factor variation with temperature for oxidized steel

Temperature [°C]	150.2	196.5
Reflectance factor *L*	43.89	39.8
Reflectance factor ratio *L*/ρ at 100 °C	1	1.1

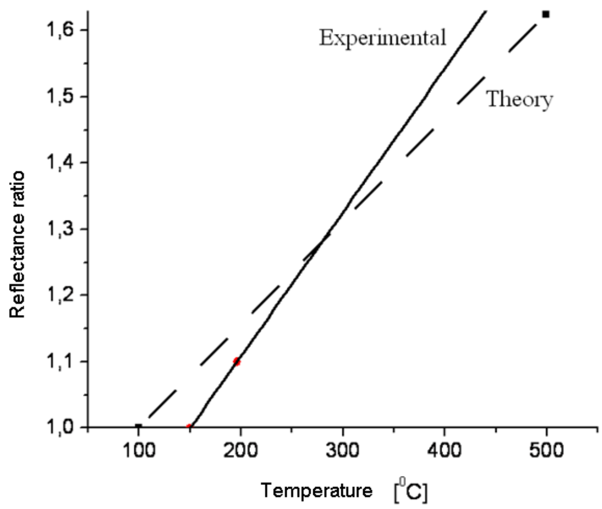


Fig. 16. Comparison between the theoretical trends of variation of reflectance factor using the temperature indicated by contact thermometer (150.2 °C) and experimental trends from selected area for histograms.

Since relative values were used, it was not necessary an initial calibration of CCD and thermal cameras. It is observed, in table 3 and figure 16 a similitude between thermal histograms analyzed in figure 4 and figure 5.

Table 3

The variation with temperature of the histogram mean ratio

Temperature [^{0}C]	76	150	158	196.5
The histogram mean ratio for CCD camera		1	-	0.9
The histogram mean ratio for Thermal camera	1	-	0.83	-

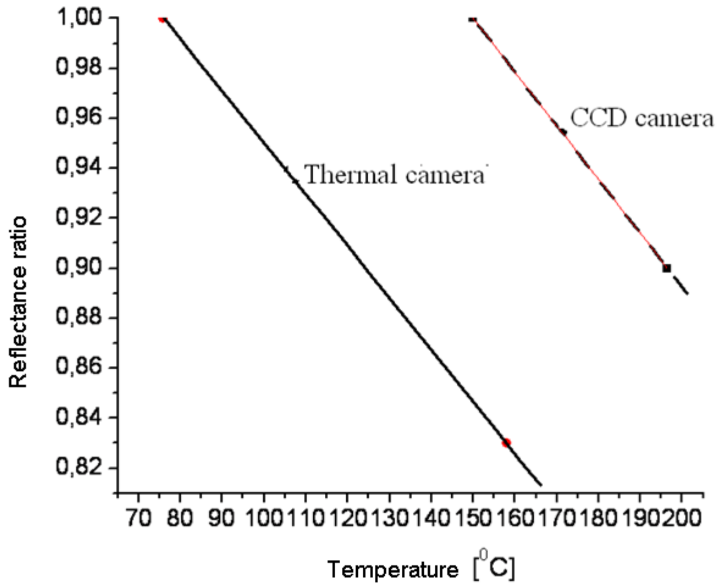


Fig. 17. Comparison between the trends of variation of emissivity (infared images from Thermal camera) and reflectance factor (visual images from CCD camera).

As long as the histogram is narrow, the better image is and with a smaller noise.

3. Conclusions

At an intensive brake, from a speed of 100 km/h, temperature of brake disc reaches high values so the disc is exposed of extremely thermal stress.

The material emissivity will have different values on disc surface for different values of temperature.

It's possible the determination of real thermal characteristics of brake disc if the variation of emissivity during the brake is known.

A correct way of evaluation the variation of material emissivity during braking, can be made by heating the disc with an external heating source.

The evaluation of emissivity variation of brake disc area made by a study of visible real image reflectance, taken with a CCD camera, has similar steps like an analysis of a thermogram for the same area.

R E F E R E N C E S

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