SOME PROBLEMS REGARDING THE INFLUENCES OF THE MATERIAL CHARACTERISTICS ON THE TEMPERATURE DISTRIBUTION IN A DISC BRAKE

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Abstract. *The paper continues previous researches of authors, where infrared images of brake disc were taken in real time experiments. A comparison between real results and the results obtained from finite element analyze in ABAQUS was made. It is observed that material properties of brake disc influence the thermal shock resistance. The thermograms analyze, obtained by experiments, makes possible to highlight the conductivity which has an essential influence over thermal stress.*

Keywords: brake disk, thermography, experimental and theoretical simulation, braking, thermal properties, cast iron

1. Introduction

Brake disc architecture design and optimization activities are followed by theoretical simulation and experiments based on a testing methodology with its accuracy [1].

As an example ABAQUS (as a software for finite element analyze), infrared thermal camera (as a precise experimental acquisition device of thermal distribution) and histograms of thermo grams (as a testing methodology).

Every research activity, in simulation and experiments, has the aim to study the phenomenological and analytical of braking in order to obtain new information regarding the resulting thermal energy from disc brake (figure 1 and 2).

For a high efficiency of brake disc, the resulted heat must be fast released, taking into account the cumulative rise of temperature [2], having unwanted effects over thermal stress thus resulted [3].

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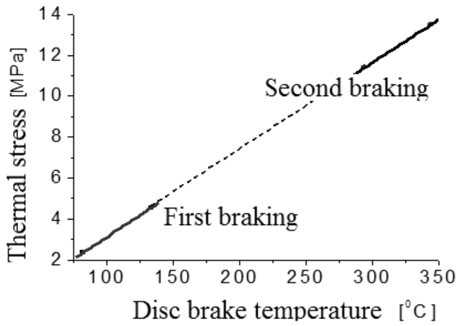


Fig. 1. Intensive braking influence over disc brake temperature. Thermal stress variation after two brakings can be linear expressed, as results of paper [**2**].

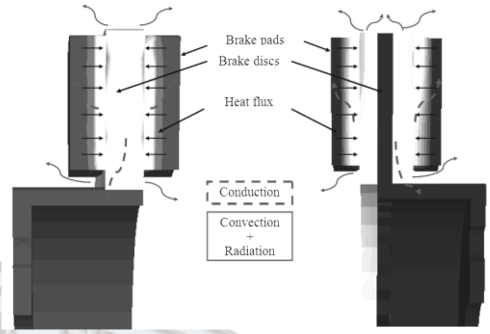


Fig. 2. The phenomenological principle of thermal energy dissipation – radiation, convection and conduction

It is mentioned, knowing thermal stress impact but having a small relevance than knowing their effects, design a durable disc brake. Forward is important to study the thermal shock as one of the significant effect of thermal stress. The thermal shock is a result of rapid temperature change during braking process, especially due to low thermal conductivity of a brake disc. The thermal stress resistance R_T can be written as [4]:

$$R_T = \frac{k\sigma_T(1-\nu)}{\alpha E} \tag{1}$$

where k is thermal conductivity, σ_T is maximal tension that material can resist, α - the thermal expansion coefficient , E - Young's modulus and ν is the Poisson ratio.

Observing relation (1), the thermal shock depends directly on conductivity. Cast iron is a common used metal for brake discs production. Its conductivity coefficient decreases with the rise of temperature [5, 6] having the effect of blocking the heat inside the disc further causing thermal shock. The quantitative evolution of thermal shock starts from heat balance corresponding to an elementary period of time dt of friction between brake disc and brake pads. Heat balance is expressed by relation:

$$Q = Q_1 + Q_2 + Q_3 \tag{2}$$

where: Q is the quantity of thermal energy as a result of braking, Q_1 – quantity of energy released by convection, Q_2 – quantity of energy released by radiation, Q_3 – quantity of energy dissipated by conduction inside the brake disc.

The risk of thermal shock is higher with a high heat quantity not dissipated. Due to the importance of the equation (2) further analyses of thermal properties of brake disc material are made:

- ***thermal conductivity*** $k\,[\mathrm{W/(m\cdot K)}]$, defined as the amount of heat flux that would pass through a certain material depending on the temperature gradient over that material and can be written [6]:

$$k = \alpha \cdot \rho \cdot c_p \tag{3}$$

where α – thermal diffusivity, $\rho\,[\mathrm{kg/m^3}]$ - material density and c_p – specific heat;

- ***specific heat*** $c_p\,[\mathrm{J/(kg\cdot K)}]$, an intensive property which means that it is independent of the mass of a substance, defined as the amount of heat required to raise the temperature of one gram of a substance by one Celsius degree; for cast iron, after [7] $c_p = 420\ \mathrm{J/(kg\cdot K)}$;

- ***thermal diffusivity α*** [m^2/s] is defined as the ratio of thermal conductivity to heat capacity; after [6] cast iron has $\alpha = (0.12...0.18)\cdot 10^{-4}[\mathrm{m^2/s}]$;

- ***emissivity ε*** of a material is defined as the ratio of energy radiated to energy radiated by a black body at the same temperature. For polished cast iron, after [7], for a temperature of 24 °C, the emissivity is $\varepsilon(24°\mathrm{C}) = 0.64$.

A connection between first three characteristics is given by relation [2, 6]:

$$\alpha = \frac{k}{\rho \cdot C_p} \tag{4}$$

Forward, the authors will establish some relations between all four material characteristics.

2. Influence of material properties over heat balance

2.1. The influence of convection over the heat balance

Quantity of thermal energy Q_1 released to environment by convection can be written [**7**]:

$$Q_1 = h_{med} \cdot A_s \cdot (T - T_a) \tag{5}$$

where:
h_{med} - the medium convection heat transfer coefficient [W/(m^2 K)] into the [$T…T_a$] and A_s - the surface area of the disc brake [m^2].

As an example, for (T - T_a) = (250-20) °C; $A_s = \frac{\pi D^2}{4} = \frac{\pi(0.25)^2}{4} = 0.05\ \mathrm{m^2}$, for a variation of $h_{air} = 10...100\ \mathrm{W/(m^2K)}$, results

$$Q_1 = (10...100)\cdot 0.05 \cdot 230 = 115...1150\ \mathrm{W};$$

admitting

$$h_{environment\,air} = 50\ \mathrm{W/(m^2 \cdot K)},$$

results $Q_1 = 575\ \mathrm{W}$ the thermal energy transformed in time interval d*t*.

Thermal energy released by convection is not dependent by material properties; it depends on dimension and geometry of brake disc.

Facts that influence the heat release by radiation and dissipation by conduction – a bigger radius – a bigger mass m and a good dissipation by conduction:

$$Q_3 = m \cdot c_p (T - T_a) = k \cdot A_s \cdot (T - T_a) \cdot g \qquad (6)$$

where *g* – brake disc thickness.

Noyes and Vickers with their experiments [**7**, p. 27] concluded, at that time, the loss of heat by convection is significant (60%)

2.2. Radiation influence over brake disc heat balance

Thermal energy quantity Q_2, dissipated, depends on local temperature *T* and emissivity coefficient ε.

Overall, total thermal energy radiated Q_2 [Watts] in a time period d*t* can be written due to Boltzmann's equation:

$$Q_2 = \varepsilon \cdot \sigma \cdot A \cdot T^4 \qquad (7)$$

where $\sigma = 5.67\times10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$ is Stefan-Boltzmann constant;

For a temperature

$$T = 250\ ^\circ\mathrm{C};\ A_s = \frac{\pi D^2}{4} = \frac{\pi(0.25)^2}{4} = 0.05\ \mathrm{m}^2 \ \text{and}\ \varepsilon = 0.4$$

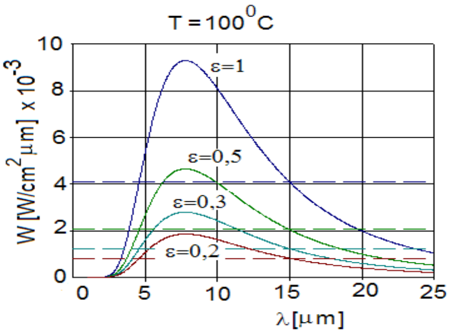
results the thermal energy in time period d*t*

$$Q_2 = 0.4 \cdot 5.67 \cdot 10^{-8} \cdot 0.05 \cdot 250^4 = 88\ \mathrm{W}.$$

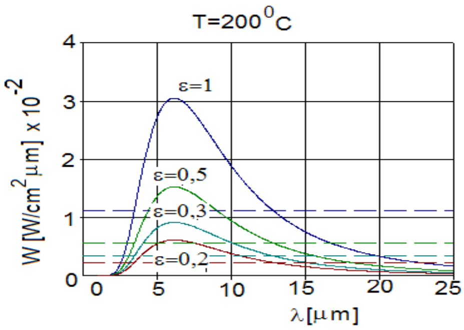
Hence, by radiation, a small part of thermal energy is dissipated, the rest of it is accumulated in disc and without conduction dissipation thermal stress appears.

The material properties and the machinability of brake disc, have influence over the incertitude of intuitive estimated studying figures 3-6.

Figure 5 presents images and their histograms for three values of emissivity 1, 0.7, 0.5. Figure 6 presents the variation of luminosity with emissivity (for each histogram's mean).



a.



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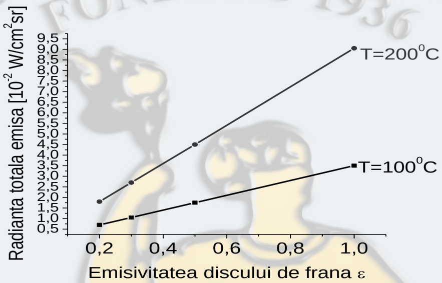


c.

Fig. 3. The influence of radiated thermal energy of brake disc (expressed by its radiance) for two temperature values a) 100 °C, b) 200 °C and four emissivity values ε(1; 0,5; 0,3 and 0,2). Both figures show the necessity of correct emissivity estimation, bigger errors of emitted radiance appear at high values of brake disc temperatures (c).

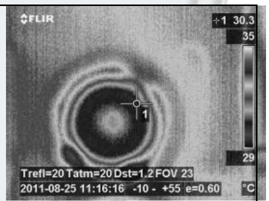
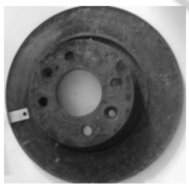
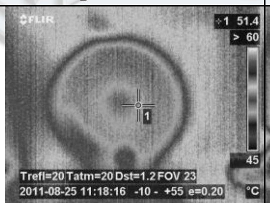
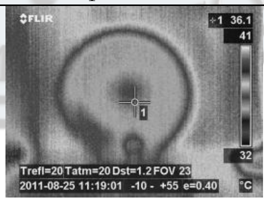
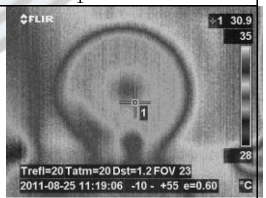
 Polished brake disc	 Emissivity 0.2 T_1 =49.3 °C	 Emissivity 0.4 T_1=35.3 °C	 Emissivity 0.6 T_1 =30.3 °C
 Rusty brake disc	 Emissivity 0.2 T_1 =51.4 °C	 Emissivity 0.4 T_1=35.1 °C	 Emissivity 0.6 T_1 =30.9 °C

Fig. 4. Correct emissivity setting and material state influence over thermo grams. With a high roughness, the temperature variation is smaller and relatively uniform. As a conclusion, at high roughness, thermal stress for different areas of brake disc is smaller.

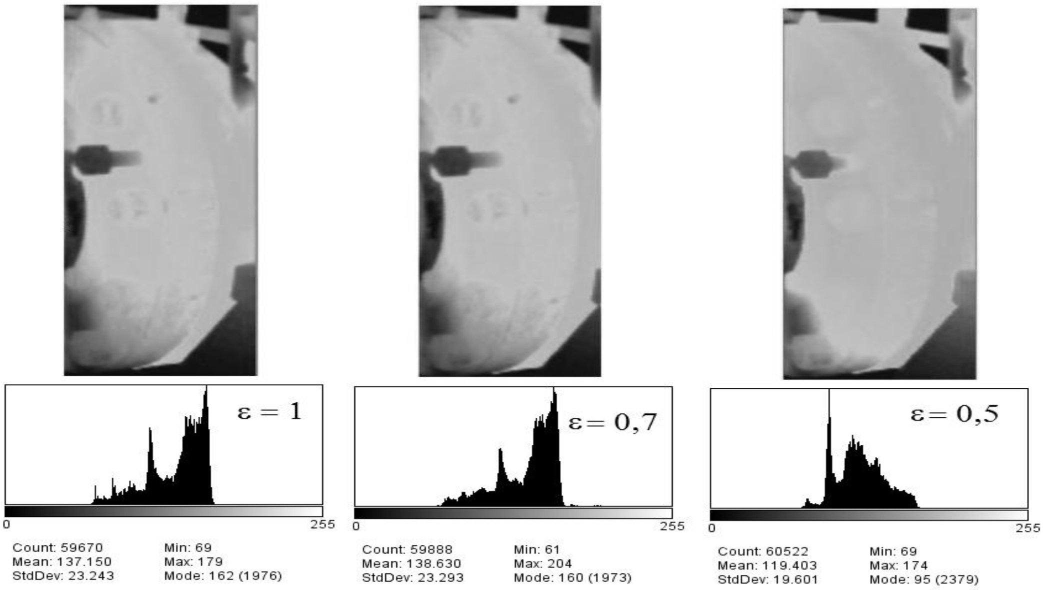


Fig. 5. Images and their histograms with three set values of emissivity ε(1; 0.7; 0,5).

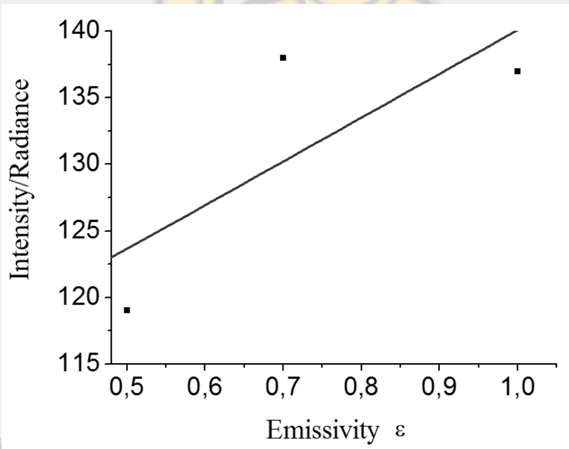


Fig. 6. The variation of luminosity with brake disc emissivity

2.3. The influence of conduction over heat balance

Conduction represents the heat transfer by means of molecular agitation within a material without any motion of the material as a whole. If one end of a disc brake has a high temperature, then energy will be transferred down to the hub which is colder. The first end has a high speed of particles that will collide with the slower ones with a net transfer of energy to the slower ones.

Thermal energy Q_3 dissipated by conduction is quantified by thermal conductivity coefficient *k*. The coefficient depends, too, on material characteristics and disc brake treatments.

For heat transfer between the two plane surfaces of the disc brake, such as heat loss through the wall of a house, the rate of conduction heat transfer is:

$$\frac{Q_3}{t} = \frac{kA(T_{hot} - T_{cold})}{g} \qquad (8)$$

where *A*-area, *d*-thickness of barrier, Q_3-heat transferred in time *t*. Total thermal energy Q_3 in a time period can be expressed by relation:

$$Q_3 = k \cdot A \cdot T \qquad (9)$$

An example is: $T = 250\,°\mathrm{C}$; $A_s = \frac{\pi D^2}{4} = \frac{\pi (0.25)^2}{4} = 0.05\ \mathrm{m}^2$ taking into account relation (2), results:

$$k = \alpha \cdot \rho \cdot c_p = 0.3 \cdot 10^{-6}\ 1/\mathrm{K} \cdot 1800\ \mathrm{kg/m^3} \cdot 420\ \mathrm{J/kg \cdot K} = 0.22$$

More over $Q_3 = 0.22 \cdot 0.05 \cdot 420 = 88\ \mathrm{W}$

For a high temperature, the accumulated heat is released more by radiation and less by conduction, than a low temperature. Once with the temperature the molecular event grows too and the conductivity coefficient comes down. Thus, figure 7 presents a graphic resulted from experiment results in paper [6].

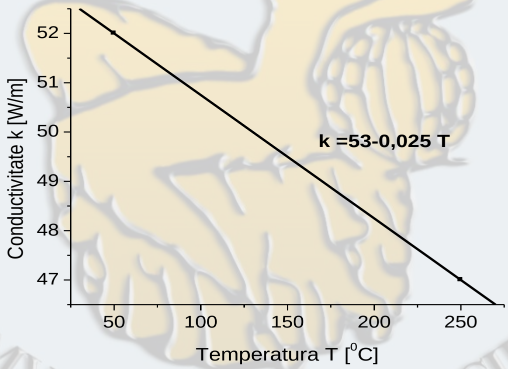


Fig. 7. Thermal conductivity as a function of temperature for a cast iron, after [**6**].

For short period of braking (4÷6 seconds) a mean value of conductivity can be considered (49…50).

The dependence of *k* coefficient, on material characteristics and brake disc machinability, can be determined from diagrams of figure 8. This figure presents temperature variation in time for two types of cooling for vented brake disc. This temperature variation was made to determine emissivity variation after a methodology presented by him in paper [8]. Pedrag and al. in paper [1] used a similar methodology to determine conduction coefficient.

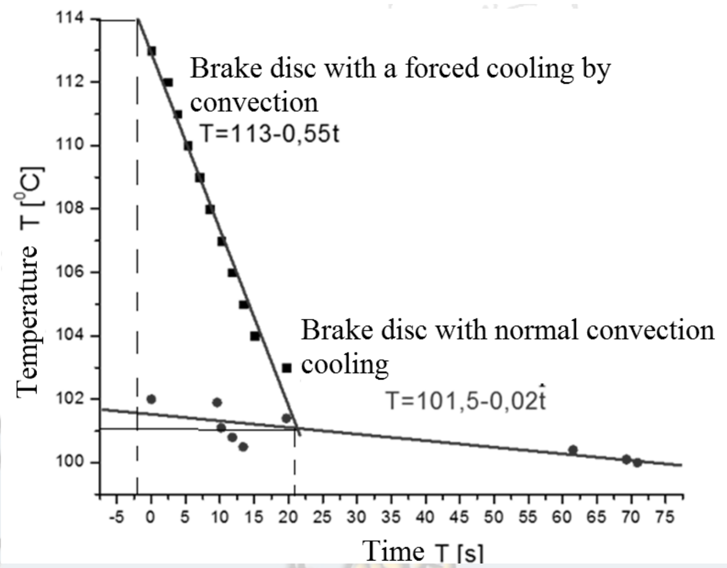


Fig. 8. Temperature variation for two types of cooling.

For cast iron , thermal conductivity k is quite high, and between usual temperature met at first braking (under 250 °C) varies between 40…50, as a function of temperature value *T*. At a given temperature, thermal conductivity is proportional to the raise of temperature. This behavior is quantified in the Wiedemann-Franz Law:

$$k = \sigma_e \cdot L \cdot T \qquad (10)$$

where Lorentz's number *L* is 2.44×10^{-8} W Ω K^{-2} and σ_e – electric conductivity of brake disc material.

3. Approach the ideas

3.1. Supplementary ventilation of brake disc

Thermal stress is defined by relation:

$$\sigma = E \cdot \alpha \cdot \Delta T \qquad (11)$$

It's more important its time variation:

$$\frac{d\sigma}{dt} = E\left(\frac{d\alpha}{dt} \cdot \Delta T + \alpha \frac{d(\Delta T)}{dt}\right) \qquad (12)$$

Due to small braking period (approximately 4 seconds) high thermal conductivity and emissivity modifications occurs.

From figure 7, taking into account relation [9]:

$$k = \frac{q}{4\pi}[\ln t_2 - \ln t_1]/[T_2 - T_1]$$

It is established

$$k = \frac{q}{4\pi}[\ln t_2 - \ln t_1]/[T_2 - T_1] \approx \frac{q}{4\pi}\frac{\ln 20,5 + -\ln 5,5}{101,9 - 101} = \frac{q}{4\pi}\frac{4.7}{0.9} \cong 5.22 \cdot \frac{q}{4\pi}$$

For high ventilation (forced) results:

$$k_{ventilation} = \frac{q}{4\pi}[\ln t_2 - \ln t_1]/[T_2 - T_1] = \frac{q}{4\pi}\frac{\ln 20,5 + \ln 5,5}{114 - 101} = \frac{q}{4\pi}\frac{4.7}{13} \cong 0,36 \cdot \frac{q}{4\pi}$$

The ratio

$$\frac{k}{k_{ventiltion}} = \frac{5.22}{0.36} = 14.5 .$$

A strong decrease of conductivity appears in case of forced cooling by ventilation. The temperature rise can be a phenomenological explication of this, for the same period of time.

A rise of conductivity was expected but the molecular event was high due to high rise of temperature and the effect is reverse – a lower conductivity.

For the vented brake disc, the conduction is smaller, local temperature is higher so the heat will be dissipated by radiation.

An analyze of the ratio variation was made: $\frac{Q_2}{Q_3} = \frac{\varepsilon \cdot \sigma \cdot A_s \cdot T^4}{k \cdot A_s \cdot T} = \cdot\sigma(= \text{const}) \cdot \frac{\varepsilon \cdot T^3}{k}$.

From equations (6), (7) and (9):

- For a thick disc (a bigger mass) the coefficient k is smaller for the same quantity of thermal energy Q_3, see equation (3);
- For a high temperature, the coefficient ε is smaller for the same accumulated thermal energy Q_1 see equation (7);
- From figure 7. and due to ratio $\frac{\varepsilon}{k} = \frac{\text{const.}}{T[\text{K}]^3}$ for $T \in [50...250], k \notin [52...47]$, the coefficient k = 53-0.025 T;
- For constant ratios $\frac{Q_2}{Q_3} = \frac{\varepsilon \cdot \sigma \cdot A_s \cdot T^4}{k \cdot A_s \cdot T} = \cdot\sigma(= \text{const}) \cdot \frac{\varepsilon \cdot T^3}{k}$, for intensive braking from 100 km/h ... 50 km/h (where brake disc temperature is under 250 °C), the emissivity and conduction varies in opposite ways by temperature (figure 9).

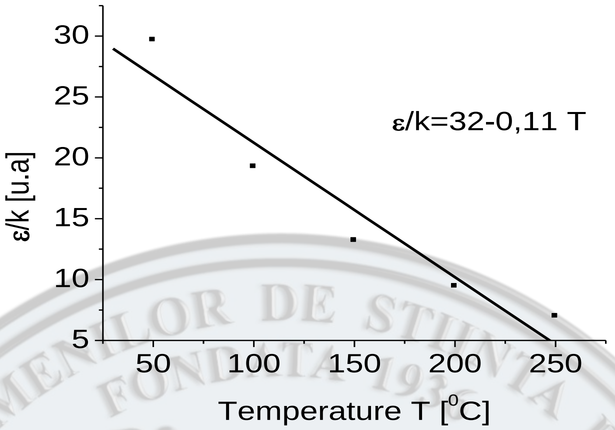


Fig. 9. The ratio variation $\frac{\varepsilon}{k}$ in relative units reported to temperature variation.

Similar variation of conductivity with temperature is given for steel [10, 11].

Must be mentioned, from paper [12] the high effect of thermal stress appears in the first 4 seconds of the braking.

3.2. Numerical and experimental analyze. Results interpretation

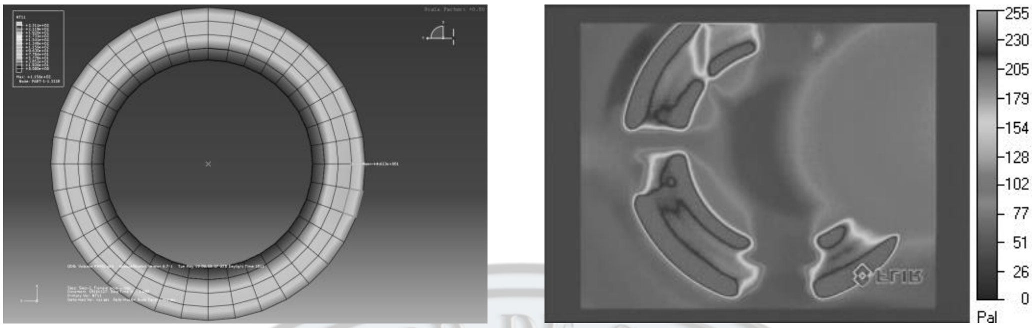
Nowadays traffic is characterized by a high density of motor vehicles and intensive braking, especially at town entrances, from usual speeds of 100 km/h ... 60 km/h.

Due this, a disc brake must be efficient and must permit a fast stop of motor vehicle in 2÷6 seconds [2] from a speed of 100 km/h. An example is given by a braking period of 5.48 seconds for a Volvo motor vehicle at a temperature of 27 °C [2]. Considering the high effect of thermal stress in the first seconds of braking [12], the authors in their finite element analyze considered a braking period of 4 seconds.

Due to previous results of experiments made and previously published by the authors, the research continued with a finite element analyze, made in ABAQUS.

The aim of these was to validate an interrelation between emissivity experimental determined and thermal simulation of conductivity with mentioned software.

To validate results, a comparison between images obtained from experiments and simulation was made. Thermal images were processed with MikroView [13] and Termografie [14]. The comparison was made for two velocity values 80 km/h and 50 km/h (figure 9, 10 and 11). Temperature repartition is non-uniform in radial direction due to high convection and radiation to surface extremities.

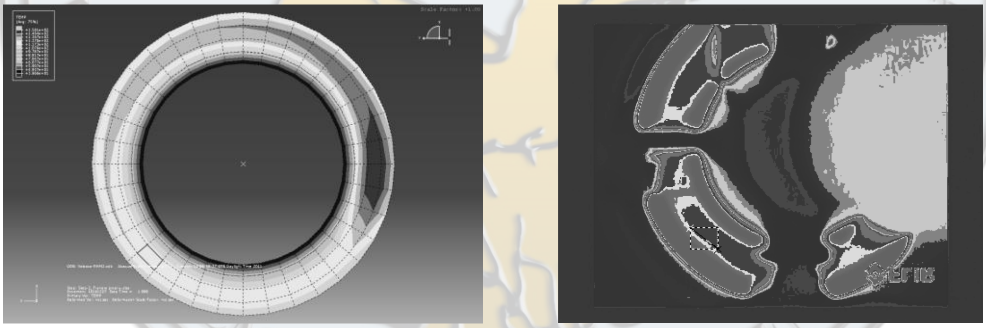


a. analyse with ABAQUS **b.** analyse with MikroView

Fig. 9. Temperature repartition over disc surface at 80 km/h.

a. analyse with ABAQUS **b.** analyse with MikroWiew

Fig. 10. Temperature repartition over disc surface at 50 km/h.



a. analyse with ABAQUS of temperature in elements – the selected element temperature is 143 °C **b.** analyze with Termografie

Fig. 11. Temperature repartition over disc surface at 50 km/h.

Figure 11.a presents an element of modeled brake disc which has a temperature of 143 ^{o}C. The thermal image (Fig. 11.b) was processed with software named Termografie which made possible to select an area identical as position to one obtained by simulation. For that area the temperature was 147 ^{o}C.

The results of this comparison are in good concordance (the error between experiment and simulation results are about $\varepsilon = \frac{147-143}{147} \cdot 100 = 2,72\%$).

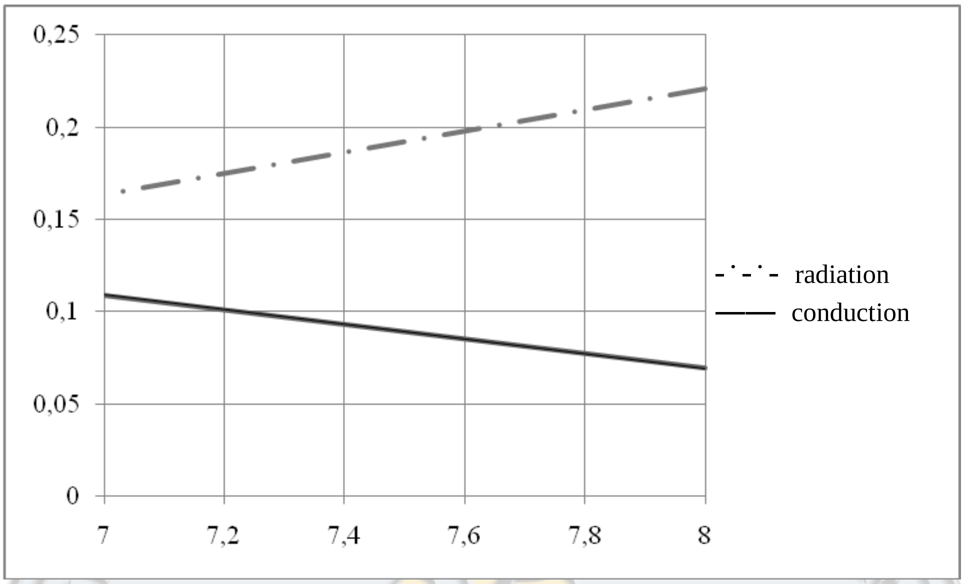


Fig. 12. Thermal energy transfer due to radiation and conduction as a function of thickness.

4. Conclusions

1. Thermal properties of brake disc material are important in establishing braking efficiency.
2. Convection influences thermal stress by brake disc radius - the bigger it is, the limit thermal layer is higher and thermal bridging takes place at the disc periphery.
3. Conduction is significant influenced by temperature evolution for an intensive braking; the conduction coefficient comes down with temperature and emissivity rise.
4. Having emissivity variation is possible to know conductivity variation in heat balance due to dependence between appreciation errors of both characteristics; thus the conductivity variation can be followed like the emissivity variation.
5. Emissivity variation at a moment can be highlighted by luminosity of thermal image; the same variation of luminosity permits the evaluation of brake disc material's conductivity and forward to thermal stress.

REFERENCES

[1] Predrag D. Milenković, Saša J. Jovanović, Aleksandra S. Janković, Milan D. Milovanović, Nenad D. Vitošević, Milan V. Djordjević, and Mile M. Raičević, *The Influence of Brake Pads Thermal Conductivity on Passenger Car Brake System Efficiency*, THERMAL SCIENCE, Vol. 14, Suppl., pp. S221-S230, **2010**.

[2] M. Z. Akop, R. Kien, M. R. Mansor, and M.A. Mohd Rosli, *Thermal stress analysis of heavy truck brake disc rotor*, Journal of Mechanical Engineering and Technology, vol. 1, no. 1, July-December, **2009**.

[3] Marko Reibenschuh, Grega Oder, Franci Cus, Iztok Potrc, *Modelling and Analysis of Thermal and Stress Loads in Tray Disc Brakes-Braking from* 250 *km/h to Standstill*, Strojniski vestnik-Journal of Mechanical Engineering 557-8,494-502, **2009**.

[4] http://www.efunda.com/materials/elements/TC_Table.cfm?Element_ID=Fe.

[5] W. L Guesser, I. Masiero, E. Melleras, C. S. Cabezas, *Thermal Conductivity of Gray Iron and Compacted Graphite Iron Used for Cylinder Heads*, Rev. Mat., Vol. 10, no. 2, pp. 265-272, ISSN 1517-272, June **2005**.

[6] Rena L. Hecht, Ralph B. Dinwiddie, Wallace D. Porter, Hsin Wang, *Thermal Transport Properties of Grey Cast Irons, SAE 962126"* at http://www.osti.gov/bridge/servlets/purl/391701-W8xmvM/webviewable/391701.pdf.

[7] Arthur Stephens, *Aerodynamic Cooling of Automotive Disc Brakes*, a thesis submitted in accordance with the regulations for the degree of Master of Engineering School of Aerospace, Mechanical & Manufacturing Engineering RMIT University, March **2006**.

[8] Spulber, C., Voloacă, Ş., *A contribution on experimental determination of emissivity variation of a disc brake by image analysis*, The 6th international colloquium "Mathematics and Physics in Engineering, Numerical Physics and Complexity" joint with the 2nd International Colloquium "Physics of Materials", University "Politehnica" of Bucharest, Romania, 8 october **2010**; Annals of the Academy of Romanian Scientists, Series on Science and Technology of Information, Vol. 3, No. 2, pp. 61-72, **2010**.

[9] Spulber, C., Voloacă, Ş., *Uncertainty of the disc brake thermal stress measured by thermography*, Annals of the Academy of Romanian Scientists, Series on Science and Technology of Information, Vol. 4, No 1, pp. 111-123, **2010**.

[10] Peter Blum, *PP Handbook*, cap. 8, pp. 8-11, November **1997**.

[11] Vikas Adarsh Narang, *Heat Transfer Analysis in Steel Structures*, a thesis submitted to the Faculty of the WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering, May **2005**.

[12] S. Koetniyom, P.C. Brooks, and D.C. Barton, *The development of a material model for cast iron that can be used for brake system analysis*, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 216, No. 5, pp. 349-362, **2002**.

[13] Ji Hoon Choi, and In Lee, *Transient thermoelastic analysis of disk brakes in frictional contact*, Journal of Thermal Stresses, 26:223-244, **2003**.

[14] *** MikroView 2.9, Software used in processing thermo graphic images, producer Mikron, SUA.

[15] *** Termografie 1.0. Software used in processing thermo graphic images, producer Datagram, Romania.