

# Numerical and experimental analysis of dry contact in pad disc brake assembly

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**Abstract.** When driving in cities, due to intensive loads, the brake disc assembly aside of mechanical and thermal stresses. Thermal stresses are the main source of risk for the braking system. In the paper, a numerical thermo-mechanical analysis was performed using ANSYS software for brake disc assembly within a hydraulic braking system. In the numerical analysis the model coupled between disc and pad was considered. In the paper were determined the total deformations, the values of Von Misses stresses and the temperature variations within a certain braking interval. In the first modelling was considered a ventilated disc made of gray cast iron and brake pads made of semi metallic material. In the second modelling was considered the same brake disc and pads made of composite material with organic fibre. The simulation models will be validated by experimental determinations on a hydraulic braking plant. Both numerical simulation and experimental determinations were performed by considering ten successive brakes. The results were used to compare the values obtained from numerical and experimental temperatures in order to validate the considered models.

## 1. Introduction

An important component in the braking system is the brake disk [1-3]. On the one hand, it has the role of slowing down or stopping the wheels of the vehicle in motion and, on the other hand, the dissipation of the heat obtained during this operation. For this purpose, on the surface of the brake discs press the brake pads by means of a mechanical force. The brake pads are made of friction material and are mounted in a calliper.

The main requirement imposed on the brake discs is to ensure a rapid dissipation of heat in the external environment. The overheating of the braking system results in decreased of braking capacity [1], [2]. In the braking process, the mechanical and thermal stresses which act on the disc and the brake pads are very large. During intensive braking that occurs when driving cars in cities, thermal stresses are the main source of risk for the braking system [4]. Also, the atmospheric conditions and the type of surface on which the vehicle is running influence the performance of the disc-pad brake assembly. All this can lead to intense wear, shape changes or damage of them. The thermal stresses that occur in intensive braking can be evaluated by analyzing the temperature distribution on the contact surface between the disc and the brake pad. So far as, the discs and brake pads are considered the essential elements which work together in the braking process, this implies [1]: friction stability over a very wide temperature range and low dependence of the friction coefficient on the contact pressure, the speed of the vehicle and the environmental condition [1].



Assessing the behavior of disc brake assembly at thermal stresses can be achieved by the comparative analysis of the temperatures obtained on numerical models during the simulation and of the temperatures obtained by experimental determinations during real time of a brake on an experimental plant [4].

In the last decades, great attention has been given to improve brake discs performance concerning its behaviour when there is in friction with the brake pads [5]. This great effort led to materials development, such as non-ferrous copper alloys, aluminum matrix composites and carbon composites [5]. Many researchers investigated the heat generation phenomenon between contact surfaces in automotive brakes to predict the temperature distribution and especially the maximum temperature during the braking to avoid failure before an estimated lifecycle. The researchers used different numerical techniques such as the finite element and finite difference methods to compute the sliding surface temperature [6-9]. Choi and Lee through the finite element method performed a transient thermal-elastic analysis of disc brakes, considering the thermal effect in modeling [6]. Faruk et al. used the finite element method to calculate the distribution of thermal stresses in a brake disc made of composite materials [7]. Ouyang et al. have shown that the temperature during braking can affect the vibration level in the brake disc assembly [8]. Gao and Lin have shown that the temperature accumulated during braking is the cumulative result of the speed, pressure, friction coefficient, thermo-physical characteristics of the materials from which the discs and the brake pads are made. All of these factors influence the durability of the pad-disc brake assembly [9].

In the paper was performed a numerical thermomechanical analysis, using the ANSYS software for the disc brake assembly within a hydraulic braking system. The analysis was performed for two cases:

- Case I: cast iron ventilated disc and semi-metallic pad;
- Case II: cast iron ventilated disc and organic fiber composite pad.

The simulation models will be validated by experimental determinations on a hydraulic brake plant. Both numerical and experimental determinations will be performed by considering ten successive brakes. The results allow comparisons between the numerical and experimental temperatures in order to validate the models considered.

## 2. Numerical and experimental procedure

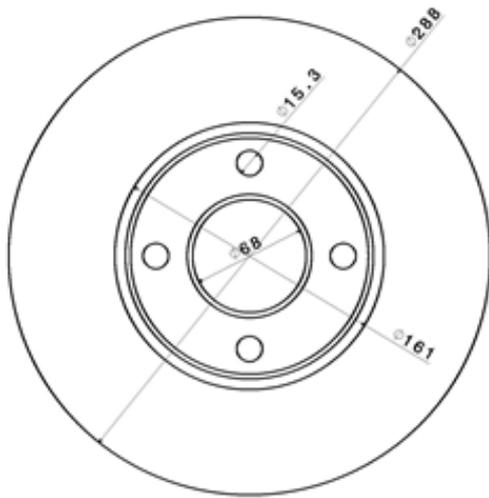
### 2.1. Dimensional characteristics and properties of materials

Figure 1 shows the dimensions of the brake disk, and Figure 2 shows the dimensions of the brake pad.

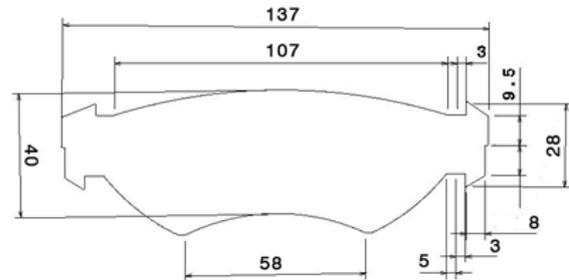
The brake disc material is gray cast iron due to the technical and economic advantages of this material. For the brake pads will be considered two different materials: one semi-metallic and the other composite with organic fibers. The semi-metallic brake pad is standardized and it is used for small and medium vehicles [10]. The composite material is a new one obtained in the laboratory, the chemical composition and manufacturing technology being the subject of other papers published at this time [11-13]. The properties of brake discs and brake pads are shown in Table 1.

**Table 1.** Properties of disc materials and brake pads considered in modelling

Type of material	Thermal conductivity ( $\text{W m}^{-1}\text{C}^{-1}$ )	Density ( $\text{kg m}^{-3}$ )	Specific heat ( $\text{J Kg}^{-1} \text{C}^{-1}$ )	Poissons ratio	Coefficient of linear expansion ( $\text{K}^{-1}$ )	Young Modulus ( $\text{K}^{-1}$ )
Disc (Cast iron)	52	7200	447	0.28	$1.1 \cdot 10^{-5}$	110
Pad 1 (Semi metallic)	60.5	7850	434	0.30	$1.2 \cdot 10^{-5}$	20
Pad 2 (Compozit)	40	1290	800	0.22	$2.6 \cdot 10^{-5}$	26



**Figure 1.** Dimensions of the brake discs



**Figure 2.** Dimensions of the brake pads

The weight of the brake disc is 7.2 kg, the weight of the semi-metallic pad is 0.557 kg and for the composite pad is 0.410 kg. The physico-mechanical and tribological characteristics of the composite brake pad were presented in [11], [13].

## 2.2. Modeling

In a braking system, the mechanical energy is transformed into a caloric energy. This energy is characterized by the total heating of the disc and pads during the braking phase. The frictional heat can cause high temperatures [1], [2]. The dissipation of the frictional heat generated is critical for effective braking performance. Temperature changes of the brake cause axial and radial deformation and affects the contact between the pads and the disc. For this reason the system should be considered as a fully coupled thermomechanical system [14].

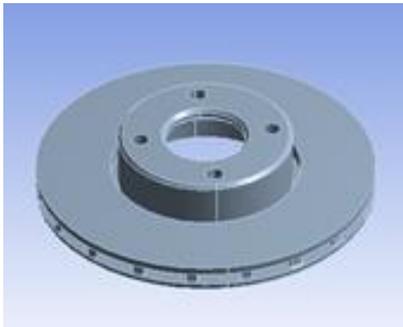
In the paper, the pad-disc assembly was modeling in two cases:

- Case I: cast iron ventilated disc and semi-metallic pad;
- Case II: cast iron ventilated disc and organic fiber composite pad.

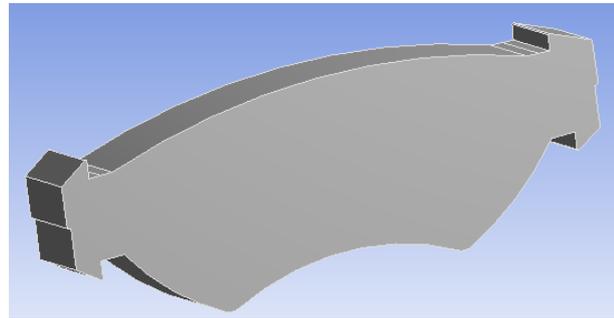
The pads and the disc brake has been designed using CATIA V5 and assembled together for analysis. These elements were imported to ANSYS Workbench for analysis the behaviour by varying material properties under different pressure. Simplifying hypotheses used in modeling are [6]:

- all kinetic energy on the surface of the brake disc is turned into heat;
- heat transfer involved for this analysis is by conduction and convection, radiation can be neglected due to the small amount that is 5% to 10%;
- brake disc material is considered homogeneous and isotropic;
- the field of analysis is considered axially-symmetric;
- inertial forces are negligible during the analysis;
- the pressure applied by the brake pad to the disc was considered uniform.

The preparation of the structural model of the disc and pad assembly was made using the finite element method. Figure 3 show the 3D model of the disc brake and Figure 4 show the 3D model of the brake pad. The boundary conditions are introduced into the ANSYS Workbench. For the disc and the brake pads, was considered a transient thermal analysis for angular speed of 150 rad/s during ten second braking period. In modelling it was considered increment of initial time 0.01s and initial temperature of the disc was 22°C, Figure 5. The structural conditions for the models consist of a fixed, cylindrical support which allows rotation around the y-axis at a constant angular speed of 150 rad/s.



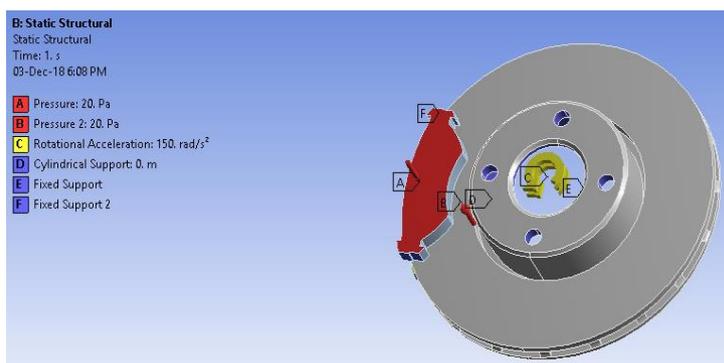
**Figure 3.** The 3D model of a ventilated brake disc



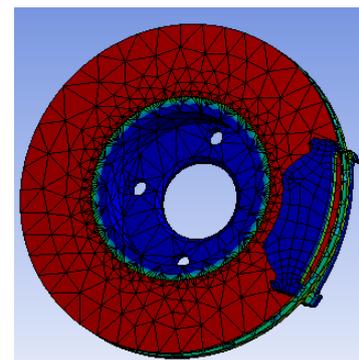
**Figure 4.** The 3D model of the brake pad

The convection coefficient was applied to the contact surface of the disc brake with the pad and it was  $250 \text{ W/m}^2\text{C}$ . In modelling it was considered the friction between the contact surfaces and the coefficient of friction being 0.3.

The finite elements used in meshing of disc and pads are tetraedric with three-dimensional elements. For disc brake there are 13450 nodes and 5718 elements and for brake pads there are 2895 nodes and 483 finite elements. Figure 6 shows the disc-pad brake assembly mesh in finite elements.



**Figure 5.** Boudary conditions on the disc-pad assembly



**Figure 6.** Meshing of brake disc assembly

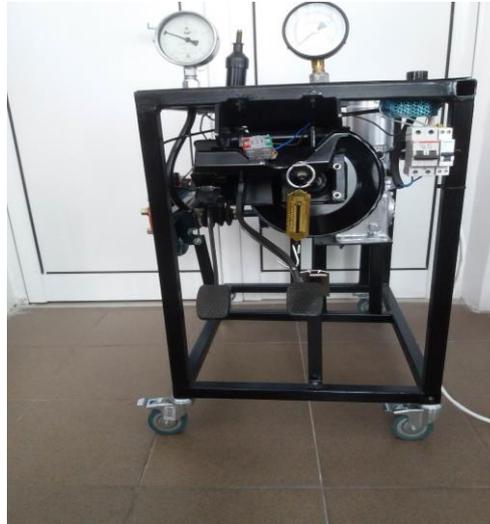
In this study, static and thermal analysis was performed on the disc-pad assembly for three different pressures of 1 MPa, 1.5 MPa and 2MPa [14]. The best configuration of disc - pad assembly has been selected based on Von Misses stresses, total deformations, heat dissipation capacity. The numerical simulation will be validated in the laboratory on the experimental plant.

### 2.3. Experimental installation for validation

Simulation is a technique for carrying out experiments with the computer, involving the use of mathematical and logical models. These models that describe the behaviour of some components of a real system over time. A validated simulation model should behave similarly to the phenomenon on which it is based. The results obtained with the simulation program will be compared with those obtained experimentally, taking into account both the measurement errors and the mathematical methods of solving. If the simulated solution approaches the experimentally solution, then the simulation model is valid.

The purpose of the experimental determinations was to obtain information about the temperatures between the disc and the brake pad during ten successive brakes. Both numerical and experimental determinations will be performed by considering ten successive brakes. The results allow comparisons between the numerical and experimental temperatures in order to validate the models considered.. In

order to validate the simulation models, was used the experimental plant shown in Figure 7. The plant allows for sustained braking, in order to analyze the laboratory behaviour of the pad-disc brake assembly. The description and operation of the plant was published in the paper [13].



**Figure 7.** Experimental plant for laboratory validation of the models [13]

Figure 8 shown the brake pad made of semimetallic material to be mounted in the experimental plant. The composite material produced in laboratory was prepared for positioning on a metal support. Figure 9 shows the metallic support and Figure10 shows the friction material.



**Figure 8.** Semi-mettalic plate



**Figure 9.** Metal support prepared for mounting the friction material



**Figure 10.** Organic fiber friction material with organic fibers

### 3. Discussions and results

#### 3.1. Numerical analysis

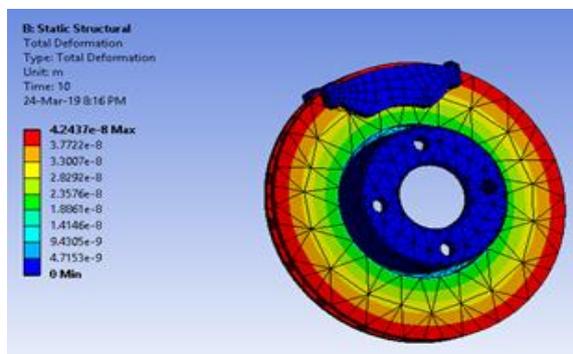
As a result of the thermo-mechanical analysis, the total deformations, the Von Misses stresses and temperature variation graphs, during the ten consecutive brakes will be presented for the pad and disc brake assembly.

The objective of considering the coupled effect of thermal and mechanical analysis is to obtain a simulation closer to the actual operating situation when the brake disc is not only subjected to the load generated by the pads but also to the expansion induced by the temperature effect [15]. In the analysis reports was obtained information about the behaviour of the pad and disc brake assembly under dry friction conditions in numerical and graphic form.

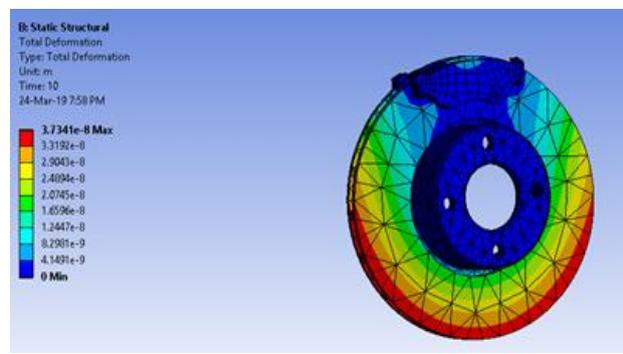
During a braking, the maximum temperature depends almost entirely on the heat storage capacity of the disc due to friction. This will generate a disc asymmetry due to the temperature rise that will cause deformation inside it [14].

The total deformations were recorded on the circumference of the disc. This phenomenon is due to the fact that the deformation of the disc is caused by the heat developed due to friction with the brake pad [15]. This may lead to the occurrence of thermal stresses overlapping the mechanical ones that lead to the cracking of the disc [16]. The thermal deformation of the disc influences the contact surface between disc and pad, thus reducing the effectiveness of the brake. Similar conclusions were made in the paper [15].

Figure 11 shown the total deformations recorded for the disc and the semi-metallic pad and Figure 12 shown the total deformations recorded for the disc and the composite pad at a pressure of 1 MPa. The deformations for the other values of the modelling pressures are shown in Table 2. The deformations in the case of the pad made of composite material are smaller than if the pad is made of semi-metallic material.



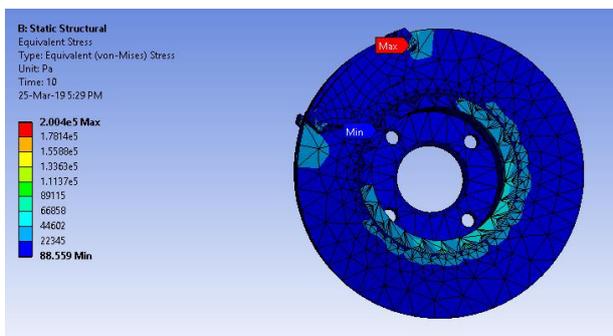
**Figure 11.** Total deformations at 1 MPa pressure for case I



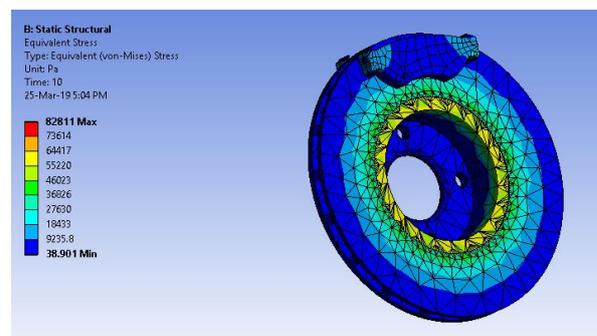
**Figure 12.** Total deformations at the 1 MPa pressure for case II

Figure 13 shown the distribution of Von Mises stress in case of semi metallic pad and Figure 14 shown the distribution of Von Mises stress in case of modelling with a composite pad, at a pressure of 1 MPa. The results obtained for the pressure of 1.5 MPa and 2 MPa are shown in Table 2.

In both variants of Von Mises stresses are distributed almost symmetrically on the front of the brake pad and on the contact surface between the disc and the brake pad. For modelling with composite pad, the maximum of Von Mises stress is lower than the case with semi metallic pad. From both figures it is observed that the maximum of Von Mises stresses were obtained to the outside of the radius of the pad. The lowest value of Von Mises stresses was obtained in the lower radius of the pad. In the modelling where the pad is made of semi-metallic material, Von Mises stresses are higher than in the case where the pad is made of composite material.



**Figure 13.** Von Mises equivalent stress for case I at a pressure 1 MPa

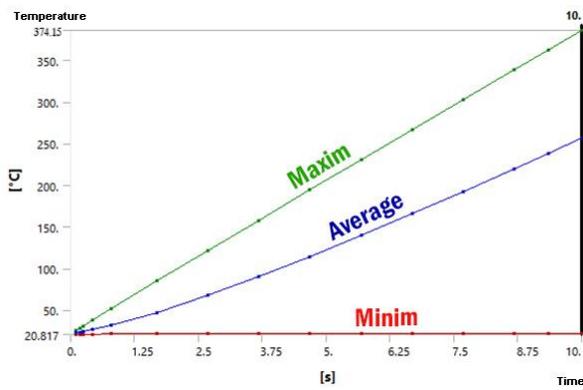


**Figure 14.** Von Mises equivalent stress for case II at a pressure 1 MPa

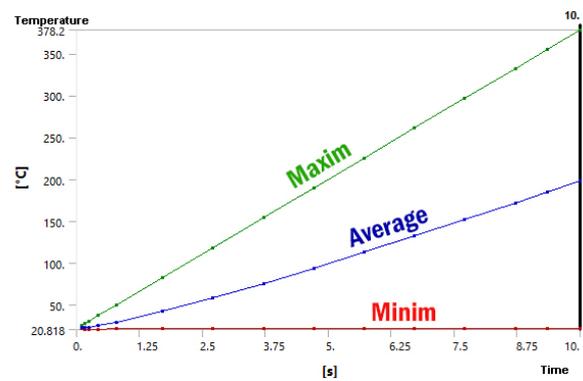
**Table 2.** Total deformation and Von Misses stresses for modelling cases

Pression ( Pa )	Total deformations (m)		Von Misses Stress ( MPa )	
	Case I	Case II	Case I	Case II
1	$4.4243 \cdot 10^{-9}$	$3.37341 \cdot 10^{-9}$	$2.0040 \cdot 10^{-9}$	$0.8281 \cdot 10^{-9}$
1.5	$4.4283 \cdot 10^{-9}$	$3.7344 \cdot 10^{-9}$	$4.9986 \cdot 10^{-9}$	$1.2174 \cdot 10^{-9}$
2	$4.4305 \cdot 10^{-9}$	$3.8993 \cdot 10^{-9}$	$6.0005 \cdot 10^{-9}$	$1.3656 \cdot 10^{-9}$

The variation of the pressing of the pad does not greatly influence the stress and strain values. Figures 15 and 16 show the temperature variation graphs over time in the simulation range, in the two cases considered. Analyzing these graphs is observed a linear increase in temperature over the ten successive brakes.



**Figure 15.** Temperature-time variation graph for semi-metallic material modelling model



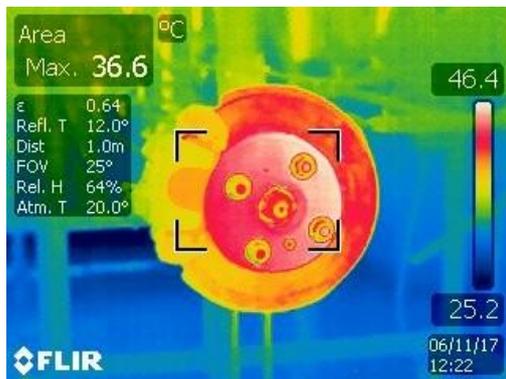
**Figure 16.** Temperature-time variation graph for composite material pad modelling

In the case of semi-metal pad, Figure 15 shows that at the end of the simulation the average temperature in the disc is 256.19°C. In the case of the composite pad, Figure 16 show that it is 161.7°C. The temperature at the end of the simulation process in the case of pad made of composite material is smaller than if the pad is made of semi-metallic material. This shows that the brake pad material influences the temperature in the contact area.

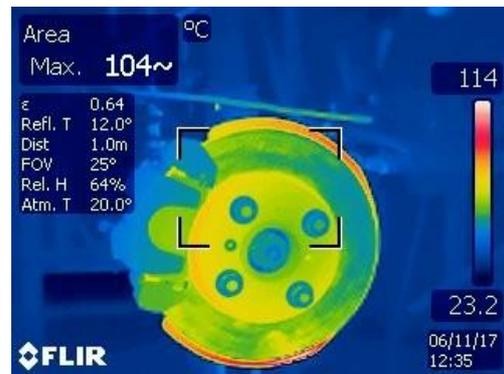
3.2. Experimental analysis

Figures 17-20 shown some of the thermograms of the temperatures recorded during laboratory experiments in case of mounting in the experimental plant a brake pad made of semi metallic material.

It is noticeable that at the beginning of the braking the temperature increased relatively quickly. To the fourth brake the temperature was 104°C, and at the end of the braking the temperature was 245°C.



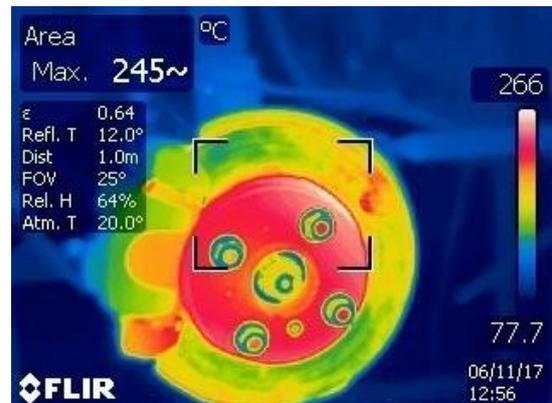
**Figure 17.** Second brake temperature



**Figure 18.** Fourth brake temperature



**Figure 19.** Temperature at ninth brake

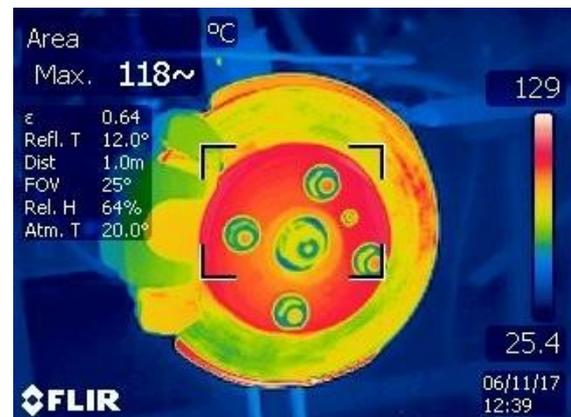


**Figure 20.** Temperature at last braking

Figures 21-24 shown some of the thermograms of the temperatures recorded during the experiments in case of mounting in the experimental plant the brake pad made of composite material.



**Figure 21.** Fifth brake temperature



**Figure 22.** Seventh brake temperature



**Figure 23.** Temperature at eight brake



**Figure 24.** Temperature at the tenth brake

In the contact area the temperature at the end of the ten brakes was 183.1°C. In both cases an increase in temperature is observed from one braking to another. The temperature at the end of the braking interval for the composite pad was much lower than the semi-metallic pad.

#### 4. Results and discussions

Table 3 presents the temperature values obtained numerically and experimentally in the two cases considered.

**Table 3.** Comparative results for temperatures in the brake disc assembly

<b>Case I: Cast iron disc - semi-metallic brake pad</b>									
<b>Temperature (<math>^{\circ}</math>C)</b>									
Braking 1		Braking 2		Braking 3		Braking 4		Braking 5	
Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.
1		1		1		1		1	
22.86	23.6	31.63	36.6	47.21	72.3	90,35	104	114.42	121.6
Braking 6		Braking 7		Braking 8		Braking 9		Braking 10	
Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.
1		1		1		1		1	
139.61	149.2	154.11	161.2	165.67	181.6	219.69	206	256.19	245
<b>Case II: Cast iron disc - composite brake pad</b>									
<b>Temperature(<math>^{\circ}</math>C)</b>									
Braking 1		Braking 2		Braking 3		Braking 4		Braking 5	
Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.
2		2		2		2		2	
22.64	35.9	24.30	38.7	42.21	51.5	67.75	69.8	75.65	77.8
Braking 6		Braking 7		Braking 8		Braking 9		Braking 10	
Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model	Exp.
2		2		2		2		2	
93.95	95.4	112.91	118	142.91	133.6	172.12	169.9	185.12	183.1

The temperature has a linear increase during the braking process, both in simulation and experimental determinations. Table 3 shows that the temperatures obtained experimental are slightly higher than those obtained in the simulation. This is explained by the fact that we have adopted a number of simplifications in the modelling process, which have led to these differences in results.

There are no significant differences between the experimental and numerical temperature values, which confirms the validity of the simulation models.

#### 5. Conclusions

In this paper were presented the analysis of the thermo-mechanical behavior of the disc and pad contact during braking with ANSYS software. In order to validate the models, experimental determinations were made in the laboratory on a hydraulic braking plant. The findings from this study are:

- the finite element method has highlighted the areas most exposed to mechanical stresses as well as the temperature developed in the contact area between the disc and the brake pad;
- large deformations take place in the outer radius area of the brake disc;
- consideration of the thermal effect in modelling shows that the temperature has a significant effect on the behaviour of the contact surface of the disc and pad brake assembly;
- the pressure on disc has little influence on Von Misses stresses and deformations;
- both in numerical simulation and in experimental determinations, the temperature, Von Misses stresses and total deformations of the composite brake pad were lower than for the semi-metallic pad;
- the temperature range is influenced by the thermo-physical properties of the materials from which the brake pads are made;
- experimental study validated numerical results, which showed good agreement between model and reality;
- as far as the results from the modelling are concerned, we can say that they are in line with those in the literature;

Considering the brake disc assembly, from the point of view of the thermo-mechanical analysis we can say that the most favorable case is the one with the brake pad made of composite material.

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