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RESEARCH ON THE INFLUENCE OF THE VENTILATION SLOTS AND THE THERMAL STUDY OF THE BRAKE DISC

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Abstract: *Brake disc cooling is an important area of research for car manufacturers, therefore one of the most important components of the braking system is the disc. The scientific paper focused on approaching a thermally efficient design, because during the braking process, the brake disc is subject to a high thermal stress and a rapid temperature change. Within this work, three different constructive variants for the ventilated brake disc, made of semi-metallic material, were made, after which they were subjected to a thermal analysis, then for the variant which had the best values of the temperature, a ceramic material was chosen, later an analysis was made for the air circulation of the brake disc in the Fluent CFD module.*

Key words: *brake disc, thermal analysis, Ansys, temperature, ventilation, braking system.*

1. INTRODUCTION

The braking system is a necessary and crucial system for the operation of any type of vehicle and at the same time provides the safety of its passengers.

During the braking process, the disc and its components are subjected to high thermal stress, sudden temperature changes, and in order to reduce the temperatures on the surface of the disc, certain structural modifications of the brake disc have been implemented over time [1].

Ventilated discs are sized not to exceed temperatures of 600-700°C in the event of severe braking sequences. The literature shows that the use of an aerodynamic architecture at the brake disc leads to a decrease of more than 30% in the cooling time and, consequently, a decrease in thermal stress is obtained by a similar percentage [2]. Thus, limiting the temperatures reached during successive braking leads to an increase in the heat transfer capacity of the brake discs, this being achieved by achieving an adequate heat transfer [3].

There are several types of brake discs on the market, depending on their construction and the type of vehicle you will be using. Thus, for small vehicles, where the thermal demands are much lower, the full brake disc is often used. The most common and used types of discs on the car market are ventilated or ventilated-perforated brake discs, which help in higher braking performance and support higher temperature values [4].

Previous studies and research in this field have focused on solid brake disc models and ventilated discs.

A good functioning of the braking system largely depends on the type of brake disc used and the material from which it is made, because during the braking process, due to the friction force between the disc and the brake pads, the kinetic and potential energy is transformed into thermal energy [5]. This thermal energy requires the brake disc and its components, and researchers in the field have always sought solutions for the highest possible thermal efficiency.

Numerous researchers have studied the thermal phenomena that occur in the brake disc assembly that has a direct impact on braking performance.

Their focus was on the thermal behavior of the brake discs in a transient state in the solid-ventilated variants. Based on numerical simulation, radial ventilation was shown to be essential in keeping the disc cool during braking operations [6].

The efficiency of the braking system largely depends on the absorption and release capacity of the brake disc, for the heat flow that accumulates on the surface of the disc during the operation of the braking system, but also on the ability of the system components to resist heat, and then another important factor is the coefficient of friction [3]. For this, research was carried out for the frictional contact between the contact surfaces between the disc and the brake pads, and following the simulations carried out, which were later validated with the help of some test stations for the braking system, they indicated the importance of the construction of the brake disc [5].

A measure often used and which was also considered in this work is by creating a design that is as efficient as possible from a thermal point of view. Thus, a ventilation slot was created for the heat flow, later three variants of its positioning in the structure of the brake disc were thermally analyzed [7].

The main purpose of this study is to create and perform a numerical simulation for perforated ventilated brake discs, on the influence of the ventilation slots for the thermal efficiency of the braking system. The importance of the study for the behavior of the discs during braking and the importance of the geometry of the disc for a more efficient release of the heat flow was emphasized [8].

The study of the disc geometry and the ventilation slots was followed by a finite element analysis for the thermal behavior of the disks in the ANSYS Workbench simulation program.

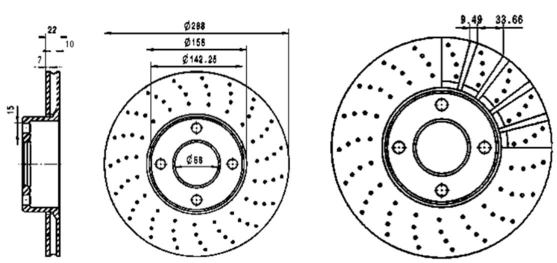
2. DESIGNED MODELS AND MODELING METHOD

Because in the automotive industry, brake discs are divided into two large categories, namely solid discs and ventilated discs, for this scientific paper the version with ventilated and perforated disc was preferred, being the most often used.

Starting from the ventilated disc, a 3D version of the real one was designed, in the CATIA V5 modeling software, three improved constructive variants were made, based on previous research and studies carried out by other researchers before.

These researches suggested that positioning a ventilation slot is a feasible method that would allow the flow of heat that is resulted during the braking process to be dissipated in the shortest possible time and in the most efficient way, so as not to affect the vehicle [2]. At the same time, the perforations that are placed on the surface of the disc also bring a plus for releasing the resulting heat.

Figure 1 presents the main dimensions of the analyzed brake discs, which has an outer disc diameter of 288 mm. Another important dimension that was considered is the thickness of the brake discs, which in this work is 22 mm, and the inner diameter where the disc will be positioned on the hub is 68 mm.



a) Overall dimensions of brake disc
b) The dimensions of the ventilation slot

Fig. 1. Overall dimensions.

Regarding the thickness of the brake discs, all the three constructive variants chosen for the thermal and CFD simulation have a thickness of 22 mm.

All disc variants presented in the following chapter present perforations for additional cooling. The diameter of these perforations on the contact surface of the disc is 2 mm.

The constructive variants of discs analyzed are:

- Brake disc with bi-directional ventilation = A1

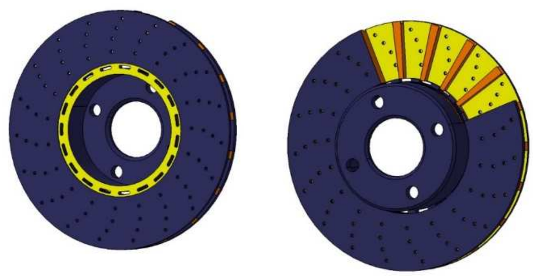
-Brake disc with rear ventilation slots = A2

-Brake disc with front ventilation slots = A3

2.1 Brake disc with bi-directional ventilation

The constructive variant created has a complex geometry, and from a functional point of view, it has a superior advantage, because the slots lead to a ventilation on both surfaces that are subject to thermal stress, both on the front and on the back.

Following other research, it was concluded that the wheel hub is another area subject to thermal action, and to avoid this, this constructive version has ventilation channels on both surfaces [5]. The width of the ventilation channel for the front surface is 3.88 mm, and for the back surface, it is smaller, only 3.5 mm, for the reasons mentioned above.



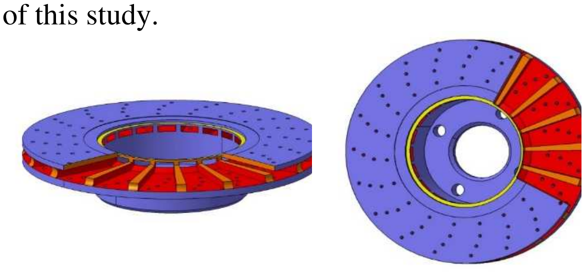
a) Brake disc b) Ventilation slots

Fig. 2. Bi-directional ventilation disc.

2.2 Brake disc with rear vent slots

For the second option, a different approach was used for the positioning of the ventilation channel, so that the heat flow has a different route.

This version proposes a way out for the heat flow on the outer side of the disc, towards the outside environment, and the other way is towards the hub of the disc. Thus, the influence of the position of this channel on the other components of the braking system will be followed and the establishment of a thermally efficient model, which is also the main purpose of this study.



a) Brake disc b) Ventilation disc

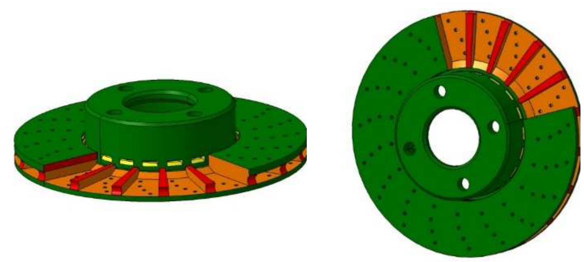
Fig. 3. Rear ventilation slots disc.

2.3 Brake disc with front vent slots

The last option chosen for the thermal study has a similar design to the previous one, but the main difference is the position of the ventilation slot, which goes through the entire surface from its edge to the inner surface, where the disc is mounted on the wheel hub.

A comparison was made between this version and the previous version, with the rear ventilation slot, because the two versions are similar from a constructive point of view.

Following the constructive analysis of the position of the ventilation channel, each variant comes with an improvement of the heat flow path and to provide lower temperature values, which lead to faster cooling.



a) Brake disc b) Ventilation slots

Fig. 4. Front ventilation slots disc.

3. SOLUTIONS AND APPROACHES USED

3.1 Braking system and components

The entire braking system is the totality of the elements in the assembly of a car that have the role of reducing its speed, partially or until it comes to a complete stop, as well as keeping it stationary after shutdown [1]. This is achieved by the transformation of kinetic energy into heat, by friction and its efficient dissipation by the components of the braking system.

The role of this braking system in the construction of vehicles is:

• reducing the speed of the vehicle to the desired value or even stopping it.

The operating principle of the braking system is based on the transmission of the force of action, exerted by the driver on the pedal, the liquid closed in the system installation and using the pressure developed in the liquid mass to actuate the brake cylinders [3].

The creation of the brake disc-pad assembly is a very difficult process. In this sense, researchers continue to find a transient thermal behavior of the brake disc during braking applications, the brake assembly component is schematically presented in Figure 5.

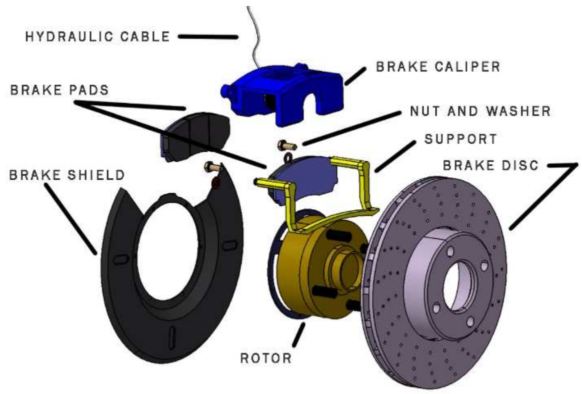


Fig. 5. Brake system assembly components.

There is always the need for the existence of a certain hypothesis for the model of any complex geometry. In modeling we always ignore things that have less importance and a reduced impact on the analysis. The assumptions considered in the modeling are always dependent on the details and accuracy required in the modeling.

The simplifying hypotheses used in the modeling are:

• all the kinetic energy on the surface of the brake disc is transformed into heat [8];

• the heat transfer involved for this analysis is by conduction and convection, radiation can be neglected due to its small amount which is 5% to 10%;

• the material of the brake disc is considered homogeneous and isotropic; the domain of analysis is considered axial-symmetric [2];

• the initial temperature was 22°C;

• the pressure applied by the brake pad on the disc was considered uniform.

3.2 Alternative materials for brake discs

For the initial phase of the thermal analysis, all the previously analyzed discs had the same standard material, the semi-metallic one.

After the first phase of the thermal analysis, where all the modeled disc variants had the same type of material, the influence of the type of material applied for each individual disc will be followed, which another type of material used in the analysis offer the best thermal behavior for the brake assembly.

Thus, choose the best constructive version of the disc, from the point of view of the temperature value, obtained after the initial analysis.

The first alternative material used will be ceramic. Thanks to its improved thermal properties, this material offers better behavior in thermal demands for modeled discs.

Ceramic brake discs are one of the newest automotive options available today. This product is composed of a dense ceramic material that is embedded with copper fiber to give it a level of friction resistance when the brakes are applied during use [2].

Table 1

Physical-mechanical properties for ceramic material

Property	Unit	Value
Density	kg/m^3	2450
Poisson's coefficient	-	0.3
Tensile strength	MPa (N/mm^2)	20 ... 40
Modulus of elasticity	GPa	30
Bending strength	MPa (N/mm^2)	50 ... 80
Elongation at break	%	0.3
Thermal shock resistance (K')	W/m	> 27.000
Thermal stability	$°C$	1350
Maximum operating temperature	$°C$	900
Linear coefficient of thermal expansion	K^{-1}	2.6 ... 3.0
Thermal conductivity	$W/(m \cdot K)$	40
Specific heat capacity (cp)	$J/(kg \cdot K)$	800

The physical-mechanical properties of the ceramic material are presented in Table 1 above and in Table 2 for the semi-metallic material, initially used for all three geometric models.

From the point of view of the thermal properties that it has, the ceramic material offers the best values, given the fact that it is often preferred in the automotive industry and for its performance still higher.

Table 2

Physical-mechanical properties for semi-metallic material

Property	Unit	Value
Density	kg/m^3	7850

Isotropic coefficient	$C^{-1}(1/C)$	0.000001.2
Young's mode	Pa	20,000,000,000
Poisson's coefficient	-	0,3
Bulk's mod	Pa	1.666700000
Shear mode	Pa	7.69230000
Tensile strength	Pa	2.500000
Compression resistance	Pa	2.500000
Bending resistance	Pa	4.600000
Isotropic thermal conductivity	$W/m \cdot K)$	60,5
Specific heat	$J/(kg \cdot K)$	434

3.3 Contour conditions and thermal analysis

In many problems, the following contradictory situation appears: on certain portions of the boundary of the domain, boundary conditions are imposed both for the natural variables and for the essential ones, or at this point they are specifying both primary and secondary variables; such a point is called a singular point [9]. To solve such situations, the essential boundary conditions (the boundary values of the primary variables) are imposed, neglecting the natural boundary conditions (the boundary values of the variables failure).

It is very difficult to model exactly a brake disc, although from a dimensional point of view it has relatively small dimensions, but the phenomena that take place in the process of its operation are extremely complex, due to the transient thermal behavior during braking [4].

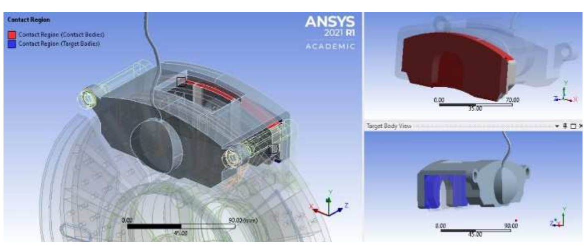


Fig. 6. Contact conditions for brake pads.

Contact conditions were imposed between all the contact surfaces of the component parts for the braking assembly, the most important of which are shown in Figure 6. Practically, these contact conditions make the link between the piece.

In addition to these constraints already presented, there are also others, between smaller component parts, such as between the washer and the clamp nut, between the edge of the hydraulic cable and the hydraulic cylinder for the caliper.

In order to perform a real thermal analysis from the point of view of the results and viable, it is necessary to choose the area where the thermal load is applied from the whole assembly that will be subjected to the analysis.

Thus, select the areas subject to loading, according to Figure 7, which in this case are the outer surface of the brake disc and the outer surface of the brake pads.

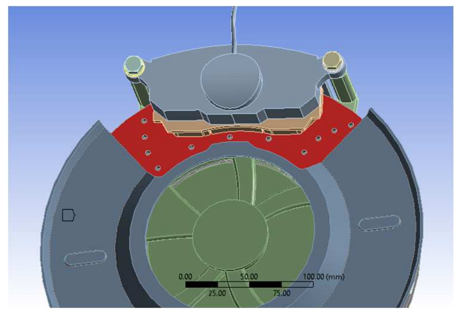


Fig. 7. Contact conditions for brake disc.

The brake disc constraints are: fixed support on one side of the disc and 20 Pa pressure on the other side.

The development of the physical and mathematical model of a machine organ presupposes the adoption of some simplifying hypotheses, which lead to the simplification of calculations, but give the results a certain degree of accuracy [9].

The energy balance of the braking process shows that almost all the kinetic energy of the vehicle is transformed into thermal energy, the whole process is presented in Figure 8 [9].

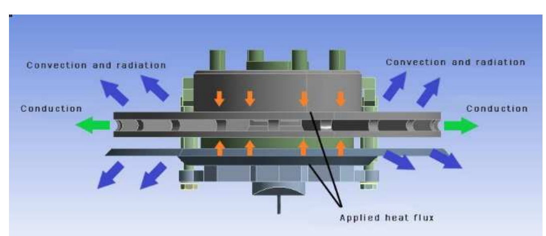


Fig. 8. Heat transfer mechanism within the brake assembly.

The large amount of heat that is released during braking contributes to the dropping of the braking qualities of the vehicle and accelerates the wear of the friction gaskets, drums, and brake discs.

3.4 Numerical analysis of the air flow for the brake disc-pad assembly

In the framework of this chapter, the air circulation around the brake disc-pads assembly will be followed, for the three constructive variants created. This type of analysis will be performed using ANSYS calculation program, in the Fluent CFD module.

During this step, from the whole braking system, it was reduced to only the brake disc and the brake shield, for the adequate result, only the analysis of the flow between the brake shield and the disc was followed.

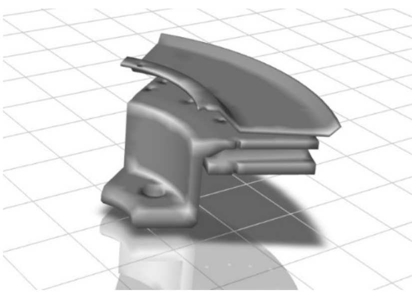
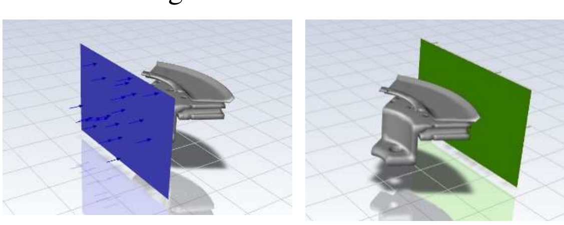


Fig. 9. Brake disc-brake shield assembly.

The geometry of the parts (brake disc and thermal shield) was studied to oppose the least aerodynamic resistance, as in Figure 9 is presented their views, according to the 3D model created for each part.

It was taken from the entire braking system studied in the previous chapter, as part of the thermal analysis, and then it was reduced to a constructive form as simple as possible. Later, in order to determine the air flow circuit, two domains were created, respectively the input domain and the output domain of the air flow, presented in Figure 10.



a) Entrance domain b) Exit domain

Fig. 10. Air flow domains.

The main purpose of this CFD analysis is to study and predict the effect of different design parameters on the aerodynamic performance of a disc brake assembly [9].

These objectives are achieved by performing CFD analysis of the airflow through the rotor passage using ANSYS Fluent and by studying the following aspects of the flow that affect the aero-thermic performance of the set that are the same follows:

- mass flow through the rotor passage;
- flow of the air line through the vent.

Next step was to create a chamber to cover the entire model for analysis. This chamber was assigned the air flow path, respectively, the entrance and the exit. The space between the inlet and outlet represents the air flow circuit.

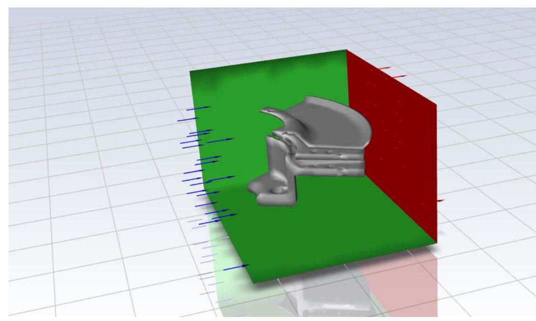


Fig. 11. The chamber for the analyzed assembly.

The properties of the material that will be used to calculate the circuit will be applied, in our case, it is air. They can be found in Table 3.

Table 3

Air properties

Property	**Value**
Density	1.225 kg/m3
Specific heat	1006.43 k/(kh K)
Thermal conductivity	0.0242 W/(m K)
Viscosity	1.7894e-05 km/(m s)
Molecular weight	28.966 kg/kmol
The coefficient of thermal expansion	0

4. FINAL RESULTS AND DISCUSSIONS

4.1 Disc thermal results

The first results presented are for the version with the thermal shield mounted, the maximum temperature obtained after the analysis was 202.32°C, presented in Figure 12. It is visible that due to a more complex geometry and due to the additional ventilation slot, the lowest temperature was obtained among all the three constructive variants studied.

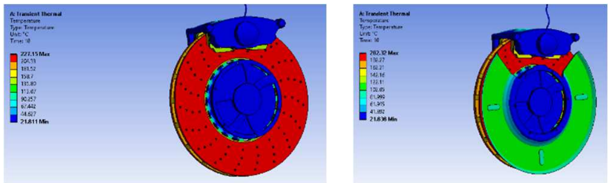


Fig. 12. Thermal results for bi-directional slots disc.

For the version without the mounted thermal shield, of the A1 brake assembly, Figure 12 shows the maximum value of the temperature obtained from the thermal analysis.

The maximum temperature obtained for this variant is 227.15°C.

The next constructive variant analyzed was the one with the ventilation channel penetrated-back, but with the thermal shield mounted in the frame of the braking assembly (A2), the maximum temperature value obtained is presented in the Figure 13., which is 238.62°C.

The thermal shield was also taken into consideration for this constructive variant, the value of the maximum temperature of the disc for this variant is represented, which is 257.39°C. The influence of the thermal shield is highlighted in this thermal analysis, since the maximum temperature value between the version with and without the thermal shield is approximately 20°C.

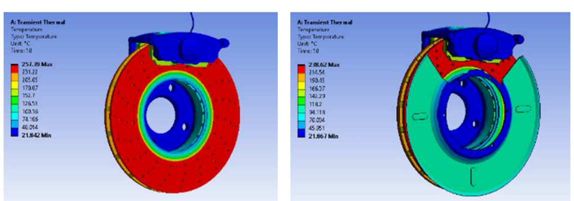


Fig. 13. Thermal results for rear ventilation slots.

The last constructive variant analyzed in the framework of this work is the one with the front-penetrated ventilation channel, this time (A3). The difference between the construction variants A2 and A3 is only the position of the ventilation channel within the disc structure.

For this constructive variant, a maximum temperature value of 252.71°C was obtained, for the variant with the mounted thermal shield, presented in Figure 14.

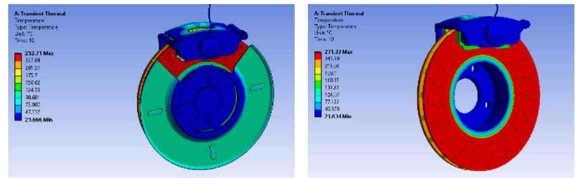


Fig. 14. Thermal results for front ventilation slots.

The constructive variant without the thermal shield achieved a maximum temperature value of 273.41°C, which is higher by approximately 20.7°C compared to the value of 252.71°C of the variants with the thermal shield on the assembly.

If an analysis is carried out from a thermal point of view, the amount of heat generated between two bodies where there is sliding leads to the thermo-elastic deformation that ultimately modifies the contact pressure distribution [6]. In order to know the distribution of the temperature, many studies have been carried for the heat generate phenomenon between the contact surfaces for the braking system components, during the brake time [10].

Following the studies and the other in the case of the work, the main indicator is that the braking shield is for the significant influence for the considered models, which is this research has only a thermal role for the braking system [3].

4.2 Alternative materials results

Thus, this work also pursued a comparative analysis of some types of brake disc construction materials, which are frequently used in this field, and in Figure 15. is presented the result of the maximum temperature values from the performed thermal analysis [2]. This thermal analysis was carried out for the best constructive variant of the three previously analyzed, so that later one thermal analysis was carried out using the A1 variant, but with the disc material being ceramic.

Following the performed thermal analysis, it resulted in a maximum temperature of 186.71°C, for the variant of the ceramic material, taken into consideration for the brake disc. This also resulted in the lowest temperature value, among the two types of materials considered in this work.

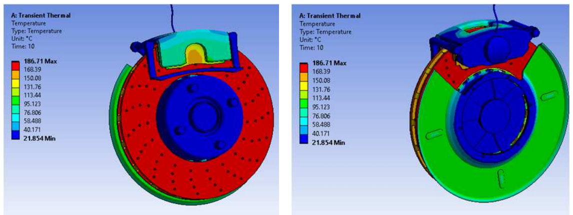


Fig. 15. Thermal results for ceramic material.

After the thermal analysis with the alternative materials used for the construction of the brake disc, it is possible to make an easier record of the individual values obtained, for each part.

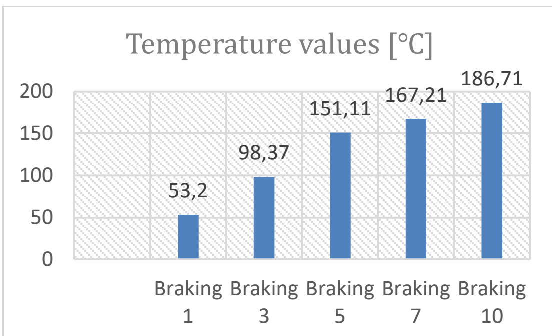


Fig. 16. Temperature values for ceramic material (during 10 consecutive brakes).

Figure 16. graphically presents the temperature values obtained for the alternative material considered for this analysis, namely the ceramic one, for the 10 consecutive brakes that were taken into account in the performed thermal analysis [11].

4.3 Air flow analysis results

Computational fluid dynamics (CFD) is a field used in the simulation of fluid flow, heat transfer and other important parameters, through numerical solution. An important element for CFD analysis is the discretization model, which must be defined as a method of equations and variables of discrete locations in space and time [12].

A more detailed analysis of the air flow speed was presented, for the three constructive variants, then in Figures 17-19 the values of the air flow speed are represented the interior of the room created for this type of analysis.

Due to the geometric shape of the model for the A1 variant, the one with bi-directional ventilation slots, it achieved the lowest speed values.

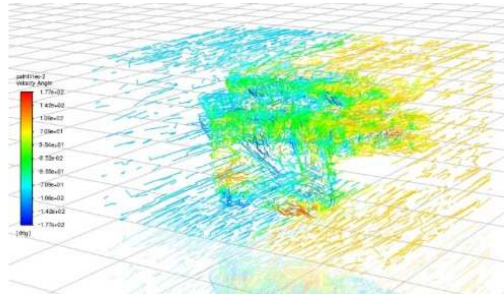


Fig. 17. Air flow parameter for bi-directional slots.

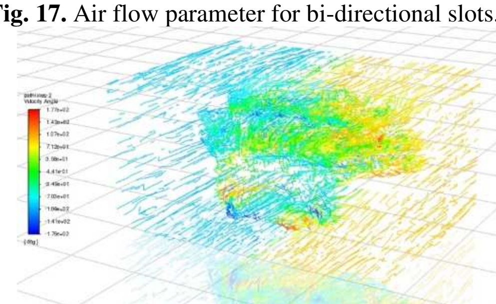


Fig. 18. Air flow parameter for rear ventilation slots.

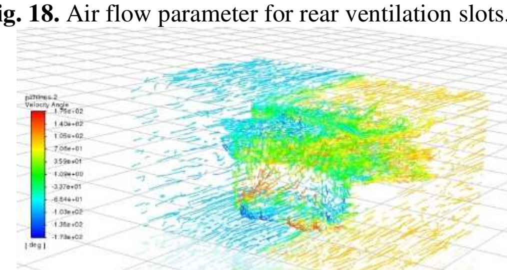


Fig. 19. Air flow parameter for front ventilation slots.

Comparing the speed distribution resulting from the numerical results, it can be concluded that the results are in good agreement. Fluent CFD analysis captures the entire complex flow circuit around the disc and the surrounding environment [12].

Figures 20-22. present the static pressure for the brake discs, starting from the construction variant A1, up to the construction variant A3.

It is visible that, due to the adopted interior design, the version with bi-directional ventilation channel achieved the highest total pressure value of 5.66^{e-03} Pa, followed by the brake disc with front ventilation slots, which had a pressure value of 5.36^{e03} Pa.

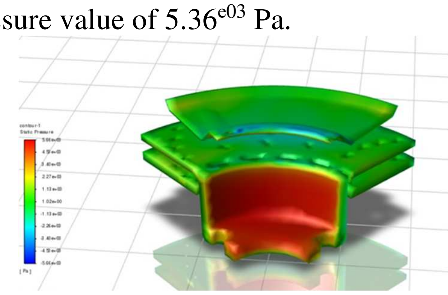


Fig. 20. Pressure parameter for bi-directional ventilation.

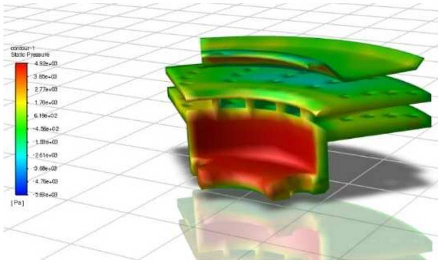


Fig. 21. Pressure parameter for back ventilation slots.

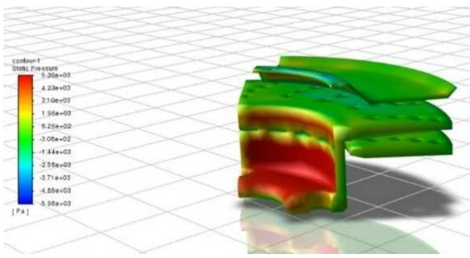


Fig. 22. Pressure parameter for front ventilation slots.

These values confirm the studies and results obtained in other specialty works, since the other variant used presents the interior ventilation channels, after which the result is smaller total.

5. CONCLUSIONS

As part of this project, three variants of different ventilation models were adopted, which were then subjected to a thermal analysis. The geometric changes help to improve the actual cooling of the brake disc assembly. By combining the CFD approach and design optimization, it was possible to study and optimize the efficiency of the braking system.

This simulation proved to be a useful tool in the design process, providing important parameters such as the velocity, pressure.

Following the results, it can be observed that the shape of the ventilation channels has a great influence on the heat exchange with the surrounding environment and the flow circuit around the braking system.

The most important conclusions after the performed analysis are the following:

- Brake disc cooling was improved when the brake shield was applied to the braking system;
- The temperature increases linearly during the braking process;
- In comparison with the alternative materials of the brake disc, the best thermal properties behavior were for the ceramic material;
- CFD simulations provide viable results, especially when comparing different brake design options;
- Regarding the results obtained from the modeling, we can say that they are satisfactory in accordance with those usually discovered in the investigations in the literature;
- Of the three variants considered in the modeling for the brake discs, the disc variant with bi-directional ventilation channel made of ceramic material has the best behavior.

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CERCETĂRI PRIVIND INFLUENȚA FANTELOR DE VENTILAȚIE ȘI STUDIUL TERMIC AL DISCULUI DE FRÂNĂ

Rezumat: Racirea discurilor de frana este un domeniu actual de cercetare abordat de producatorii auto, de aceea unul dintre cele mai importante componente ale sistemului de franare este discul. Lucrararea stiintifica s-a concentrat asupra abordarii unui design cat mai eficient din punct de vedere termic, deoarece in timpul procesului de franare, discul de frana este supus unei solicitari termice ridicate si o schimbare rapida a temperaturii. De aceea, in cadrul acestei lucrari au fost realizate trei variante constructive diferite pentru discul de frana ventilat, realizate din material semi-metalic, dupa care au fost supuse unei analize termice, iar pentru varianta care a obtinut cele mai bune valori ale temperaturii s-a ales un material ceramic, iar apoi a fost realizata o analiza pentru circulatia aerului a discului de frana in modulul CFD Fluent.

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