Thermal and fluid-dynamic analysis of an automotive disc brake with ventilation pillars aerodynamic type

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Abstract. The braking system of a car must work safely and predictably in any circumstance, which implies having a stable level of friction, in any condition of temperature, humidity and salinity of the environment. For a correct design and operation of the brake discs, it is necessary to consider different aspects, such as the geometry, the type of material, the mechanical resistance, the maximum temperature, the thermal deformation, the cracking resistance, among others. The objective of this study was to analyze the behavior of temperature, velocity and heat flow, in the ventilation duct of an automotive disc brake with ventilation pillars different from conventional using computational fluid dynamics. The SolidWorks Simulations design software was used to analyze the behavior of the fluid (air) in terms of speed and heat dissipation capacity. The numerical results for the heat flow through the ventilation channels were compared with the results obtained mathematically. The numerical results showed that the discs performed well under severe operating conditions. In the design of the brake disc is very important to select the appropriate geometry, particularly the number and the cross section of the ducts in addition to that, the type of material. Numerical methods offer advantages through the software tools for selecting geometry and material and for modeling fluid flow to optimize heat dissipation to provide maximum performance for properly maintained components.

1. Introduction

The braking system is undoubtedly the most important component for road safety of the automobile, because this depends on the total or partial detention of the vehicle, and consequently the integrity of its passengers. Generally, 70% of the kinetic energy produced in the movement is absorbed by the front disc brakes and the remaining by the rear brake, which is usually drum. These systems are based mainly on friction to stop the movement of the vehicle, having as a principle the hydraulic pressure that pushes the brake pads against the disc, which is generally manufactured from gray nodular cast iron [1,2]. Consequently, the behavior that produces this type of devices, through the kinetic energy, is to create a considerably high heat during braking, increasing the temperature by friction; this heat dissipates rapidly with the surrounding air by means of the convection phenomenon (heat transfer that occurs between masses at different temperatures) [3]. During periods of extreme braking as sudden stops or continuous, the kinetic energy is transformed into thermal energy, due to the friction between the brake rotor and the pad where temperatures are reached up to 900 °C, according to [4], 90% of heat is distributed and absorbed by the rotor; and the remainder by the pad [5]. Environmental factors are also determinants for...
the heat transfer stage to occur, and due to these behaviors, the corrosion process accelerates rapidly. In addition, when the temperature reaches high values the phenomenon appears by radiation, which also helps to dissipate the energy in the form of heat stored in the disk [6-8].

The determination of the geometric characteristics of the discs depends on the load capacity and operation, which is an important factor in the initial design phase. In most cases these designs should avoid the overheating that arises between the brake and the pad due to the effect of friction, taking into account the physical, mechanical and chemical properties that occur because in some occasions the types of materials they do not coincide correctly and have negative effects on braking efficiency [9]. In the design stage of ventilated disc brakes, it is very important to analyze the behavior of the associated thermo-fluids (surrounding air) where the characteristics and operation of the fluids on the surface of the disc can be observed, always guaranteeing the effectiveness of the process of braking and heat dissipation by the surface and the ventilation channels [10]. In a research carried out by [11], a new geometric arrangement for the optimization of air flow in an automotive brake disc is proposed, in this proposal, ventilation pillars based on National Aeronautics Committee Advisory (NACA) aerodynamic profiles (4418 and 66-219) were used, in order to perform the analysis by particle speedometer and optimize the suction conditions [12].

The heat of dissipation and the performance of the brake ventilated discs, depends largely on the aerodynamic characteristics of the air flow, through the ventilation channels and brake geometry configurations discs, which are checked by the implementation of design software that possess the library of computational fluid dynamics (CFD) [13-15]. In general, CFD applications in the automotive industry have come a long way to influence the design of automotive components, due to continuous advances in hardware and software, as well as advances in numerical techniques to solve the equations of flow fluid. The interest of the automotive industry in CFD applications derives from its ability to improve the design of automobiles and to reduce the cost of the product and the life cycle time of the products [16-18].

The study of the dynamic effects of brake discs is an important area of research for the manufacturers of the industry, as well as the academic world. The present investigation studies the behavior of air particles in an automotive disk brake with ventilation pillars type NACA type 66-209 through the numerical simulation by CFD with the help of SolidWoks Simulation software in order to evaluate the behavior of the air flow at different operating conditions of the disk, all taking into account mathematical calculation in order to optimize the systems that incur in any area of engineering.

2. Materials and methods

The kinetic and potential energy of the vehicle is quickly transformed into thermal energy generated by the brakes. Bearing in mind the above, in order for the braking system to work properly, the heat generated must dissipate as quickly as possible so that the successive brakes do not overheat and compromise the performance and safety of the system. The movement of the vehicle allows the dissipation of heat by convection and radiation. But intense (repetitive) braking causes the temperature to rise to a certain limit, known as the saturation temperature, which depends on the thermal dissipation capacity of the brake disc. In the present study, the physical and thermal properties of the disk were obtained. By performing the literature search, it was found that most of the disc brakes are nodular gray cast iron with laminar graphite, silicon and manganese, making the physical and thermal properties of this material were determined taking into account the reference of Yunus A. Cengel [19,20].

Bearing in mind the above, the profile NACA type 66-209 minimizes the resistance coefficient, commonly called the Airfoil series, which aims to minimize the resistance by ensuring a constant laminar flow, reducing the adverse pressure gradient, in addition to increasing the characteristics maximum lift. The nomenclature of this type of profiles consists of 5 digits, the number 6 being always first, referring to the series. The second digit corresponds to the location of the point of minimum pressure in tenths of the rope measured from the leading edge. The third number indicates the coefficient of support of design and finally, the last two values give the maximum thickness in percentage of the
rope. Based on the above, the designed disc brake has the following characteristics which were analyzed in the development of the SolidWorks simulations.

The following Figure 1(a), Figure 1(b) and Figure 1(c) show the selected profile with its geometry for the development of the research that was NACA type 66-209, corresponding to the series 6, with a range of maximum thickness of 9% to 45% of the length of the rope and a range of maximum curvature between 1.1% and 50% of the rope, with a coefficient of support of 0.2 and the location of the point of minimum pressure in the 60% of the length of the rope [21].

![Figure 1](image)

**Figure 1.** (a) Perfil NACA 66-209. (b) Distribution of NACA profiles on the disk. (c) Inside and outside diameter of the disc.

For the processing of the system a mesh adjusted to the unstructured solid is used, by means of the construction of irregularly distributed nodes as shown in the following Figure 2.

![Figure 2](image)

**Figure 2.** Type of mesh used in the discs.

This type of mesh allowed the correct simulation of the disc brake, without consuming so many physical resources of the computer. To perform dynamic fluid analysis in fluid areas, SolidWorks Flow Simulation solves the Navier-Stokes equations, which are formulations of the laws of conservation of mass, momentum and energy [22].

### 3. Results and discussion

Based on the proposed design of a disk brake with ventilation pillars NACA type 66-209, the heat velocities that the disks emit to the environment were determined, as we know a ventilated disc loses heat faster than a solid disk or a drum disk. To analyze this effect, the study was carried out with the Solidworks Simulations software through the CFD library, in order to have a clearer idea of the effect produced in the heat dissipation.

The physical and thermal properties of the gray nodular cast iron of laminar graphite which has a composition of silicon and manganese, were obtained from Table A-3 of the Yunus A. Cengel heat transfer book [19]: Thermal conductivity: \( k = 41 \text{ J/s} \times \text{m} \times \degree \text{C} \), Specific heat: \( \text{Cp} = 434 \text{ J/kg} \times \degree \text{C} \), density: \( \rho = 8131 \text{ Kg/m}^3 \), thermal diffusivity: \( \alpha = 11.6 \times 10^{-6} \text{ m}^2/\text{s} \), thermal transmission
coefficient: \( U = 32 \text{ J/s} \times \text{m}^2 \times ^\circ \text{C} \). The temperature rise of a brake assembly is evaluated by the following Equation (1):

\[
\Delta T = \frac{E_{\text{disc}}}{m \cdot c_p} = 38.5 \, ^\circ \text{C}
\]  

(1)

To calculate the temperature on the disc surface we use the following Equation (2):

\[
T_I - T_\infty = \Delta T
\]

(2)

Where \( T_\infty \) is the ambient temperature of 12 \(^\circ\)C, then the temperature on the surface of the disk approximately equals \( T_I = 50.5 \, ^\circ \text{C} \). What indicates that a vehicle with a mass of 1930 Kg which carries a speed of 80 km/h, circulating in an environment of 12 \(^\circ\)C, the temperature generated in the brake disc to stop is approximately 60.5 \(^\circ\)C.

Taking into account the concept of Newton's cooling based on the results obtained by [12] the brake disc after having been subjected to a temperature of 60.5 \(^\circ\)C in a braking, this disc will take an ambient temperature of 12 \(^\circ\)C in approximately 10 minutes, as long as the cooling takes place by natural convection, that is to say that the air in the environment must have a speed equal to zero.

As initial conditions for the simulation, an air flow was established whose characteristics of speed and temperature are:

- Fluid speed: 3.24 m/s
- Fluid temperature (air): 12 \(^\circ\)C
- Disc temperature: 82 \(^\circ\)C
- Material Roughness (Gray Casting): 0.1 \(\mu\)m
- Simulation Time: 60 seconds

Then, the analysis of the dynamic fluid was carried out. For this case, the air was used as a medium to determine its speed and temperature when the flow passes through the disk at the revolutions of 541 rpm and 841 rpm estimated for the present study. The SolidWorks Simulation software was used for the development of the simulations, from which the following results were obtained.

3.1. Disc at 541 revolutions per minute

It can be seen in Figure 3(a) and Figure 3(b), that the disk has the capacity to suck the fluid at a higher speed than this one. In the analysis, the fluid presents a speed of 22.22 m/s and in the area of the track it is possible to witness a speed of 30 m/s. This means that the configuration of blades at 45 degrees is optimal because by increasing the speed of the fluid, it will dissipate the heat in a better way.

![Figure 3. Fluid speed at 541 rpm. (a) Front view. (b) Side view.](image-url)
The average velocity in the suction zone is 9.33 m/s, which is high compared to proposed disc designs due to the fact that having this geometry where the leading edge of the blades is 45 degrees, the flow tends to accelerate in the area of the track, therefore, the suction zone also tends to accelerate. Likewise, the temperature of the fluid was analyzed when entering the area of the disc track, as shown in the following Figure 4(a) and Figure 4(b).

![Figure 4. Fluid temperature at 541 rpm. (a) Front view. (b) Side view.](image)

From the previous Figure 4(a) and Figure 4(b), it can be seen that the fluid increases its temperature when it is expelled from the area of the disk track, entering at approximately 12 °C it leaves more than 23 °C. This means that the heat inside the disc is carried out by the fluid allowing an optimal heat dissipation in the track.

3.2. Disc at 841 revolutions per minute

In the following Figure 5(a) and Figure 5(b), it can be seen that the fluid velocity increases in the area of the track in relation to the given speed at 541 rpm. With speeds, close to 60 m/s and wind speed of 22.22 m/s, it is shown how the geometric design with NACA 66-209 type blades with an angle of attack of 45 degrees manages to increase the speed of the fluid to dissipate the heat faster.

![Figure 5. Fluid speed at 841 rpm. (a) Front view. (b) Side view.](image)

The average speed in the suction zone is 9.83 m/s, it is 0.09 m/s higher than that shown at a revolution of 541 rpm. This speed in the suction area is high compared to conventional disc designs that hover around 5 m/s at those same revolutions per minute. In addition, the fluid temperature was analyzed when entering the disc track area, as shown in the following Figure 6(a) and Figure 6(b).

Taking into account the previous Figure 6(a) and Figure 6(b), at these rpms the fluid has the same temperature as at 541 rpm of 12 °C. It should be noted that inside the track the temperature rises so that the heat conduction goes out to more than more than 27 °C and in the discharge area it tends to go down to take the same temperature of the environment. The zone of the center is the zone of suction where they show the lowest speeds in relation to the other zones and that hover around 9 m/s or 10 m/s. The next area is the area of the track that is where the highest fluid velocities are presented thanks to the
proposed geometrical design. These speeds are around 60 m/s. Finally, the external zone is the unloading area. In this zone speeds, close to 30 m/s are presented. This means that when the flow enters the disc it is expelled at a higher speed than the one that enters and what is expected is achieved, that the fluid accelerates and guarantees a greater heat dissipation than a conventional brake disc.

![Figure 6](image)

**Figure 6.** Fluid temperature at 841 rpm. (a) Front view. (b) Side view.

4. Conclusions

Most modern road vehicles have ventilated disc brakes on all four wheels due to their effectiveness and, therefore, the heat transfer characteristics of the brake discs are interesting. Drum brakes, which can be found on the rear axles of some vehicles, are subject to problems such as lack of heat dissipation, moisture and corrosion resulting from inefficient braking because friction surfaces are enclosed and dissipation of heat is inhibited.

A numerical analysis was carried out using SolidWorks with the CFD library for the design of the brake disc with ventilation pillars type NACA 66-209 to study the air temperature inside the ventilation channels. Obtaining that at higher revolutions a greater dissipation of heat is achieved in terms of fluid velocity. On the other hand, the heat dissipation in the disc brakes depends mainly on the geometry and its ventilation channels, in addition to the operating conditions.

The heat generation and transfer calculations were made based on the maximum speed allowed on the highway of 80 km/h. Therefore, if you want to use higher speeds the disc must be tested, along with the manufacturing material and in this way, have a complete study where high temperatures and higher heat transfer will occur.

It should be noted that the model presented is still susceptible to modifications to improve the amount of air that can pass through the ventilation pillars, due to another model of pillars or the configuration of these, as well as the quantity, can provide feasible results for this studio. If another vane profile is chosen, the optimum balance between drag and lift must be studied, in addition to the methodology used to determine or quantify the flow velocity.

References

[1] García-León R and Flórez-Solano E 2016 Estudio analítico de la trasferencia de calor por convección que afectan los frenos de disco ventilados Tecnura 20(ES) 15
[2] García-León R, Flórez-Solano E and Acevedo-Peña Zoa C 2018 Análisis termodinámico en frenos de disco (Bogotá: ECOE Ediciones ltda)
[3] García-León R 2014 Evaluación del comportamiento de los frenos de disco de los vehículos a partir del análisis de la aceleración del proceso de corrosión (Ocaña: Universidad Francisco de Paula Santander)
[4] Talati F and Jalalifar S 2009 Analysis of heat conduction in a disk brake system Heat Mass. Transf. 45(8) 1047
[5] Acosta I and Pareja D 2019 Construcción de un banco de pruebas para el análisis del comportamiento al desgaste de los sistemas de frenos de disco automotrices (Ocaña: Universidad Francisco de Paula Santander)
[6] García-León R, Acosta M and Flórez E 2015 Análisis del comportamiento de los frenos de disco de los vehículos a partir de la aceleración del proceso de corrosión Tecnura 19(45) 53
García-León R, Flórez-Solano E, and Rodríguez-Castilla M 2019 Thermo-mechanical assessment in three auto-ventilated disc brake by implementing finite elements J. Phys. Conf. Ser., 1257(1) 012019

Hirasawa S, Kawanami T, and Shirai K 2014 Numerical analysis of convection heat transfer on high-temperature rotating disk at bottom surface of air flow duct ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE) 8(36142) 1

García-León R and Perez Rojas R 2017 Analysis of the amount of heat flow between cooling channels in three vented brake discs Ing. y Univ. 21(1) 71

García-León R and Flórez-Solano E 2017 Dynamic analysis of three autoventilated disc brakes Ing. e Investig. 37(3) 102

Echavez-Díaz R and Quintero-Orozco A 2017 Estudio experimental del comportamiento dinámico del fluido del aire a través de un disco de freno automotriz con pilares de ventilación tipo NACA 66-209 (Ocaña: Universidad Francisco de Paula Santander)

García-León R, Echavez-Díaz R, and Flórez-Solano E 2018 Análisis termodinámico de un disco de freno automotriz con pilares de ventilación tipo NACA 66-209 Inge CUC 14(2) 9

Chi Z, He Y and Naterer G 2009 Convective heat transfer optimization of automotive brake discs SAE Int. J. Passeng. Cars - Mech. Syst. 2(1) 961

García-León R Flórez-Solano E and Suarez-Quinones A 2019 Brake discs: A technological review from its analysis and assessment Informador Tecnico 83(2) 217

García-León R 2017 Thermal study in three vented brake discs, using the finite element analysis DYNA 84(200) 19

Dhaubhadel M 1996 CFD applications in the automotive industry (invited keynote presentation) Am. Soc. Mech. Eng. Fluids Eng. Div. FED 239(1) 473

Wurj J, Fitl M, Gumpesberger M, Väisänen E and Hochenuer C 2016 Novel CFD approach for the thermal analysis of a continuous variable transmission (CVT) Appl. Therm. Eng. 103(1) 159

Pevec M, Potrc I, Bombeck G and Vranesec D 2012 Prediction of the cooling factors of a vehicle brake disc and its influence on the results of a thermal numerical simulation Int. J. Automot. Technol. 13(5) 725

Cengel Y 2007 Transferencia de calor y masa Tercera edición (México: McGraw-Hill)

Pan L, Han J, Li Z, Yang Z and Li W 2015 Numerical simulation for train brake disc ventilation Beijing Jiaotong Univ. 39(1) 118

García-León R, Rivera López J, Quintero-Orozco A and Gutiérrez-Paredes G 2019 Análisis del caudal en un disco de freno automotriz con alabes de ventilación tipo NACA66-209, utilizando velocimetría de imagen de partículas Inf. Tec. 83(1) 10

Wei Y Wu Q Zhao X Zhang J Zhang Y 2017 An air brake model for longitudinal train dynamics studies Vehicle System Dynamics 55(4) 517