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Experimental analysis of the heat transfer generated during the operation of an automotive disc brake

R. A. García-León [a], G. Guerrero-Gómez [b] and N. Afanador-García [c]

[a]Grupo de Investigación Ingap, Facultad de Ingenierías, Universidad Francisco de Paula Santander Ocaña, Ocaña, Colombia; [b]Grupo de Investigación Gityd, Facultad de Ingenierías, Universidad Francisco de Paula Santander Ocaña, Ocaña, Colombia; [c]Grupo de Investigación Cerg, Facultad de Ingenierías, Universidad Francisco de Paula Santander Ocaña, Colombia, Ocaña, Colombia

ABSTRACT

This experimental mathematical work aims to analyse the results obtained from the heat transfer of a typical automotive disc brake and thus compare the behaviour of heat dissipation of this mechanical element under different operating conditions. The results demonstrate that the disc brakes can be used effectively in severe operational conditions with a speed of 36 km/h and an ambient temperature of 25°C, without affecting the safety of the occupants or the braking system. The use of semi-metallic pads increases the temperature over the wear track superficial temperature by around 20% more than the asbestos pad, but the material removal during sliding is around ~2.5 times more for the asbestos pad due to the coupling in the tribosystem (pad and disc brake). The heat dissipation in the disc brakes depends on the geometry of the disc, the material from which it is manufactured, the material of the pad, the weight of the vehicle, and the operating conditions, as it could be verified with the mathematical and experimental results, thus validating the contribution of the effectiveness of the braking process during its real operation.

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KEYWORDS
Temperature; disc brakes; friction; heat loss; wear machine

1. Introduction

Disc brakes are fundamental elements to maintain manoeuverability and, above all, safety in any vehicle, whether it is rotary or linear, and that of its occupants. Braking systems work by taking advantage of friction to slow down the moving vehicle through mechanical contact between two surfaces (pad and disc brake). There are currently various types of brakes, depending on the application: drum, band, disc, and conical. In particular, for the automotive sector, the most common is the disc auto-ventilated type in the front part and the drum type in the rear part (García-León, Flórez-Solano, and Acevedo-Peñaloza 2018; Asim 2014). Disc brakes differ from other types in that the applied force is normal to the disc herd and not radial, as in drum and band brakes. Another characteristic is that the friction moment does not help the actuation moment (self-energising effect), as occurs in drum and bevel brakes. This behaviour allows slight changes in the friction coefficient not to affect the braking force required to dramatically stop the car. For example, a 30% variation in the friction coefficient, which is a normal condition in humid environments, causes an increase in the force of 50%. That behaviour is why the disc brakes have occupied an important place in the automotive industry, especially in the commercial vehicle market (Wahlström 2011; Blau 2001).

During the braking process, different factors are involved in the effectiveness of this process, resulting in an interest in knowing the influence of parameters/factors such as deceleration, kinetic energy, execution force, braking force, vehicle weight, surface in contact, the coefficient friction, adhesion coefficient, vehicle aerodynamics, maximum braking force, road incline, distance and braking time, mainly by applying mathematical or simulation concepts (Kashima-University 2020; García-León, Flórez-Solano, and Suárez-Quiñones 2019; Porta et al. 2016).

McPhee and Johnson (2008) evaluated heat transfer and fluid flow using a transient experiment to quantify internal convection between the ventilation blades in terms of external convection (rotor surface) for three nominal speeds. The results showed that conduction and radiation were negligible; on the other hand, the higher the rotor speed, the heat transfer by convection increases, displaying a linear relationship. The flow aspect of the experiment involved the determination of the speed field through the internal channels on the disc (García-León and Perez Rojas 2017). García-León, Echavez-Díaz, and Flórez-Solano (2018) realised the dynamic and static analysis of a brake system with NACA 66–209 type ventilation pillars and simulated the disc brake thermal and fluid-dynamic behaviour. The results of the finite element method (FEM) analysis showed that the mathematical calculations are

CONTACT R. A. García-León ragarcial@ufpso.edu.co
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supported to validate the operating conditions of a disc brake and thus optimise the geometries and materials with which they are currently manufactured, aiding to the evacuation of the heat generated quickly compared to other types of disc brakes (García-León, Afanador-García, and Gómez-Camperos 2021).

Mazidi et al. (2011) studied the heat conduction problems of disc brake components (pad and rotor), where they mathematically and numerically modelled the behaviour of the disc brake. For the development of the numerical model, the heat transfer equations, parameters such as braking time, vehicle speed, geometries and dimensions of the brake components, the disc brake rotor materials, and the pad distribution and contact pressure were taken into account. The results show that the heat split at the contact surface of two sliding components due to thermal resistance through the accumulation of wear particles between the contact surfaces, and thus this phenomenon prevents the discs and brake lining absorbed additional heat.

Belhocine and Bouchetara (2013a) analysed the thermal behaviour of the vehicle solid and auto-ventilated disc brakes using the ANSYS simulation software. Modelling of the temperature distribution in the disc brake is used to identify all factors and the corresponding input parameters at the time of braking operation, such as the type of braking, the geometric design of the disc, and the material used, showing that the FEM analysis shows satisfactory results, compared to those of the specialised literature (Belhocine and Afzal 2019).

Topouris et al. (2019) conducted an experimental investigation on the heat dissipation of stationary disc brakes concentrated on four-disc designs: a ventilated disc with radial blades, two types of ventilated discs with curved blades (a non-perforated and cross-drilled disc), and a disc solid. The experiments were performed on a specially designed thermal spin platform and provided accurate, repeatable, and reliable temperature measurements to predict total, convective, and radiative heat dissipation coefficients. The values obtained were compared with the results obtained through computational fluid dynamics. The results showed that for the four-disc designs studied, the disc with radial blades has the highest convection heat dissipation compared to the solid disc (~30% lower). Lakkam et al. (2013) investigated the temperature gradient of the disc brake to evaluate the heat convection coefficients through experimental and numerical tests. The coefficients were modified by the change in temperature distribution in both disc brakes under forced heat convection and stable conditions. The experimental results in terms of heat convection coefficients are used in the numerical simulation through the FEM, thus studying the temperature diffusion and the thermal ventilation of the front and rear ventilated disc brakes. Consequently, the experimental results reveal that the overall heat convection coefficients of the front-ventilated disc brake are higher than those of the rear-ventilated disc. Moreover, the numerical results show that the front ventilated disc brake allows more substantial heat ventilation than its compared object, which leads to higher temperature differences between the outer and inner rotors, resulting in more heat stress, which makes it more susceptible to damage during operation.

Atkins et al. (2020) studied the local temperature of the results experimentally obtained to evaluate distributions of the heat transfer coefficient on the internal surfaces of a brake rotor with rotating blades at realistic rotational speeds. The results demonstrate that the bulk airflow within the vented channel of a rotating disk follows a predominantly backward sweep path between the pin fins. The outer surfaces generate an average cooling twice as much from the outer surface as the inner surface: this possibly exacerbates thermal stresses, which leads to thermal distortion of the rotor.

On the other hand, a Bibliometric analysis was performed about the disc brake and thermal analysis topics (research equation); the information was obtained directly from the *Scopus* database to guarantee the data quality recollected (García-Léon, Martínez-Trinidad, and Campos-Silva 2021; García-León, Gomez-Camperos, and Jaramillo 2021). As a result of the analysis of the information, Figure 1 shows the evolution of 873 articles compiled from 1969 to 2021, which were published in 354 sources by 1815 authors around the world, with an annual growth rate of 2.81% with the subject related to the heat transfer generated during the operation of an automotive disc brake which is the aim of this mathematical and experimental work.

Figure 2 shows the frequency of appearance of the 873 articles obtained and analysed, having as a trend the study of brakes, friction behaviour, brake discs, and applying the finite element method (FEM) mainly for the search equation used.

On the other hand, Figure 3 shows the relationship of the keywords in clusters presented in different colours and circles of different sizes, evidencing the frequency of use of the keywords. Note that the first cluster (green lines) is related to the study of disc brakes and the relationship with the material, thermodynamics, temperature, heat transfer, thermal stresses generated on the surface of these automotive systems. Cluster two (red lines) shows the relationship on the studies carried out on the behaviour of friction, wear, and tribology under different experimental conditions and the effect on braking efficiency; cluster 3 (yellow lines) shows the study of heat transfer and temperature on the braking system; finally, note that

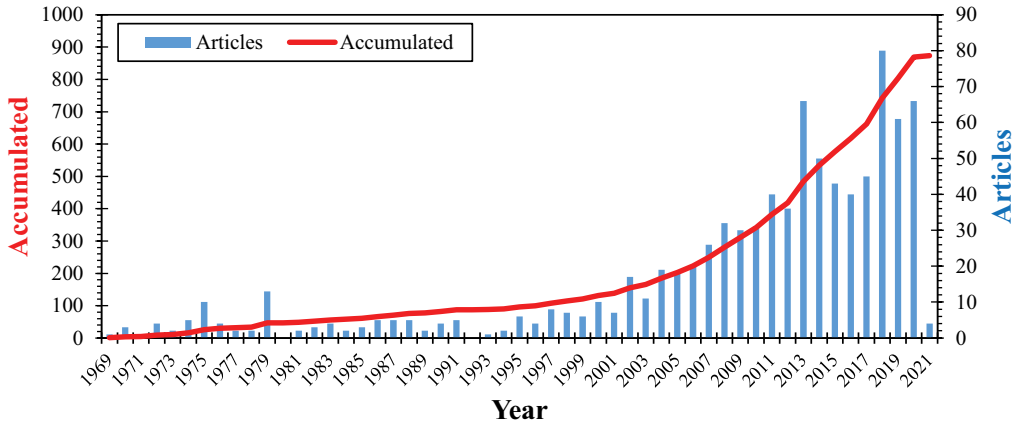


Figure 1. Evolution of the articles over the years. Source: Own elaboration.

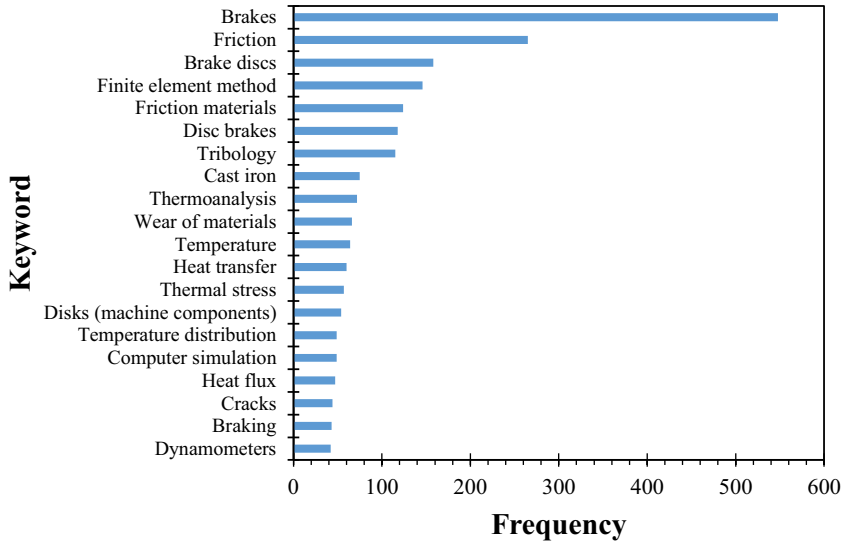


Figure 2. Frequency of appearance of keywords in analysed articles. Source: Own elaboration.

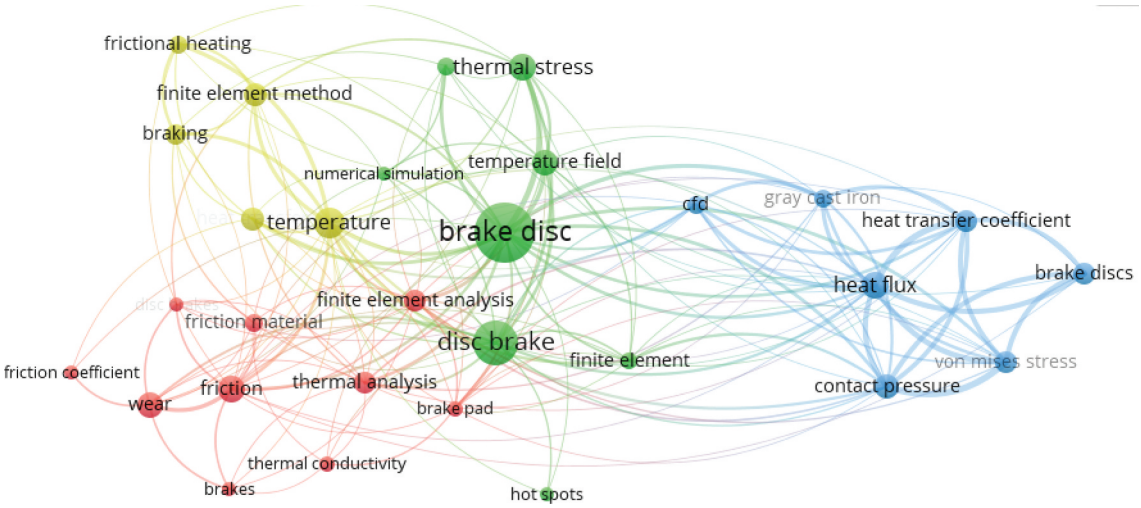


Figure 3. Relation of keywords in thematic clusters. Source: Own elaboration.

cluster 4 (blue lines) shows the relationship of the analysis by finite element method and fluid flow dynamic related to the first three clusters; thus, being of great importance the study of the behaviour of the heat transfer of disc brakes during their operation. Notice that the main influence on the study of disc brake systems is related to the wear, friction, and heat flux that involucrate temperature and, therefore, the behaviour and performance.

Considering the above, the present investigation evaluates the thermal behaviour of an automotive disc brake under the laws of heat transfer in convection and conduction phenomena using two different brake pads. Likewise, experimental results were obtained with the aid of a machine that simulates the behaviour of a braking system in order to compare the mathematical results, thus establishing optimal operating conditions for an auto-ventilated disc brake.

2. Material and methods

The braking force is the pressure that the driver exerts on the brake pedal to execute the braking process. Depending on the force applied to the pedal, a higher efficiency of the process will be obtained. Nowadays, the driver, in many cases, could not exert enough force to stop the vehicle at the ideal distance; therefore, the force is multiplied using levers or hydraulic circuits, thus obtaining a greater friction force. During real braking conditions, the maximum braking force on all four wheels of the vehicle is difficult to achieve simultaneously due to the weight distribution on the vehicle (passengers, road incline, undulations) being variable. This action determines its limit of adhesion which varies dynamically during the braking process. The weight distribution on the wheels is too variable, and the operating conditions change every fraction of a second. On the other hand, the conditions of mathematical and experimental calculations are considered suitable.

The braking efficiency is the magnitude of the braking system performance, where the vehicle must stop at a required time and distance, according to the operating conditions and the force applied on the brake pedal; in this way, the effectiveness of the braking system is considered to reach 100% when the measured deceleration is equal to the acceleration due to gravity.

2.1. Disc brake

The disc brake is the element attached to the wheel hub rotating simultaneously with the speed of the vehicle, forming the mobile element of the braking system. Against the surface or friction area of the disc brake, the pads interact with is performed to the vehicle is stopped thanks to the continuous friction that is established between the pads and the disc. Notice that during this process, the transformation of kinetic energy (accumulated in the vehicle due to its speed) into thermal energy is generated, which in many cases generates increased heat in the braking system (Reddy, Mallikarjuna, and Ganesan 2008; Jiménez García et al. 2016; Belhocine and Bouchetara 2013b). In this way, the use of self-ventilated disc brakes (with ventilation channels) is widespread today for all four vehicle wheels. Figure 4 shows the constituent elements of a self-ventilated disc brake.

In this way, a ventilated disc brake and conventional pads were used with the details shown in Figure 5. The mechanical and physical properties of the samples are presented in Table 1.

2.2. Equipment used

The tests carried out in this investigation were developed on a specially designed test machine where theories and design methods were applied. Also, the computer-aided design (CAD) was used to obtain a conceptual model of the machine, as shown in Figure 6. The experimental procedures

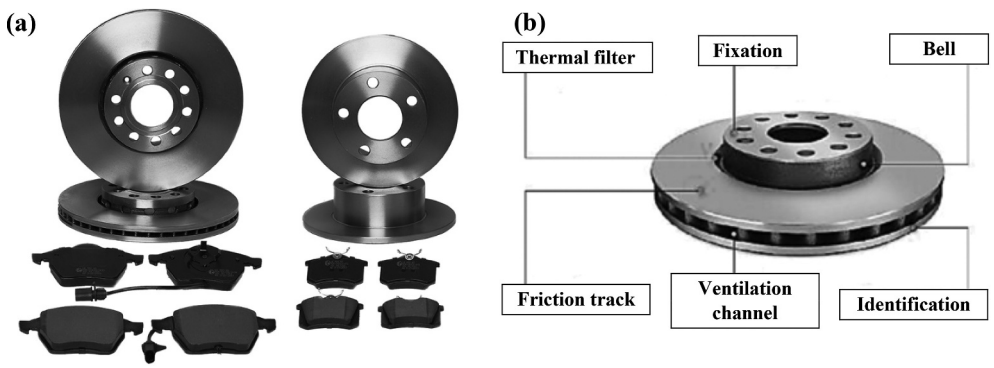


Figure 4. (a) Types of brakes and pads, and (b) Elements of a disc brake. Source: García-León, Flórez-Solano, and Acevedo-Peñaloza (2018), Kashima-University (2020), García-León, Acevedo-Peñaloza, and Rojas-Suarez (2019).

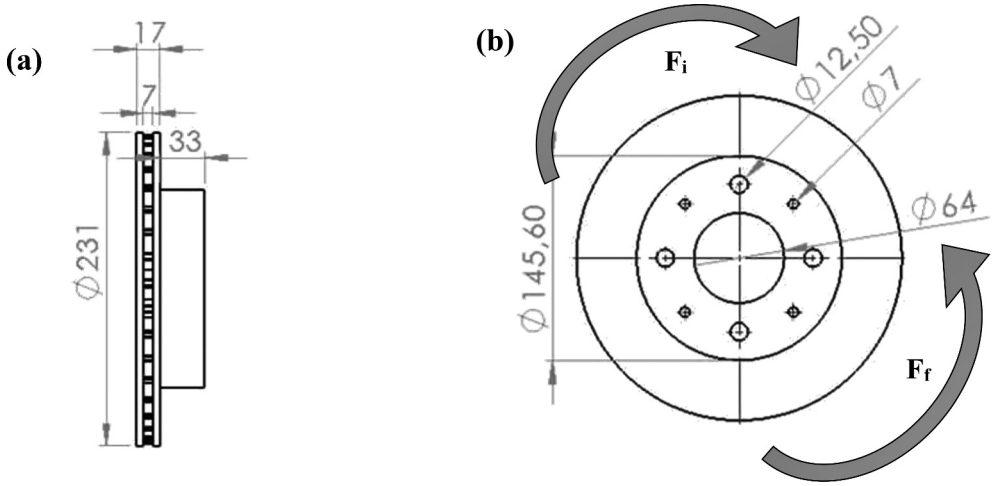


Figure 5. Inner and outer diameter of the disc brake (Measurements in mm). (a) Side view, and (b) Top view. Note: Fi is the driving force, and Ff is the braking force. Source: Own elaboration.

Table 1. Main mechanical and physical properties of brake pads and brake.

Property	Pad		Brake
	Asbestos (C1)	Semi-metallic (C2)	Gray cast iron
Brinell hardness (BH)	101	92	170–250
Shear strength (MPa)	5.46	2.45	151
Impact resistence(J/mm^2)	0.11	0.07	2.0
Coefficient of friction	0.40	0.43	0.30–0.50
Thermal conductivity (J/KgK)	0.54	1.46	2.14

Source: Ibhadode and Dagwa (2008), García-León, Flórez-Solano, and Rodríguez-Castilla (2019).

contemplated the following conditions during the test: braking pressures from 22 to 45 PSI with sampling times from 60 to 330 s. Furthermore, the temperature generated in the disc brake and the pad were taken directly from the surface with the aid of a CALEX/ST640 digital pyrometer. Likewise, after each experimental test, the Renishaw/OMI-2T equipment was used to measure the friction wear generated on the disc brake surface in contact with the pad.

2.3. Heat transfer theories

The dynamic analysis of the brake system was carried out, starting from the calculation of the particles in motion, and in this way, determining operating conditions mathematically. Notice that all equations were obtained from García-León, Flórez-Solano, and Acevedo-Peñaloza (2018), García-León, Afanador-García, and Gómez-Camperos (2021), García-León (2017) from different bibliographic sources. Initially, was consider the calculation of the braking force taking into account Equation (1):

$$F_f = W \times \left(\frac{a}{g} - F_r\right) = (m_v \times g)(\mu - f_r) \quad (1)$$

To calculate the braking force, it is necessary to calculate first the resistance and the rolling coefficient with Equations (2) and (3):

$$R_r = F_r \times W \quad (2)$$

$$F_r = 0.01 \times \left(1 + \frac{V}{160}\right) \quad (3)$$

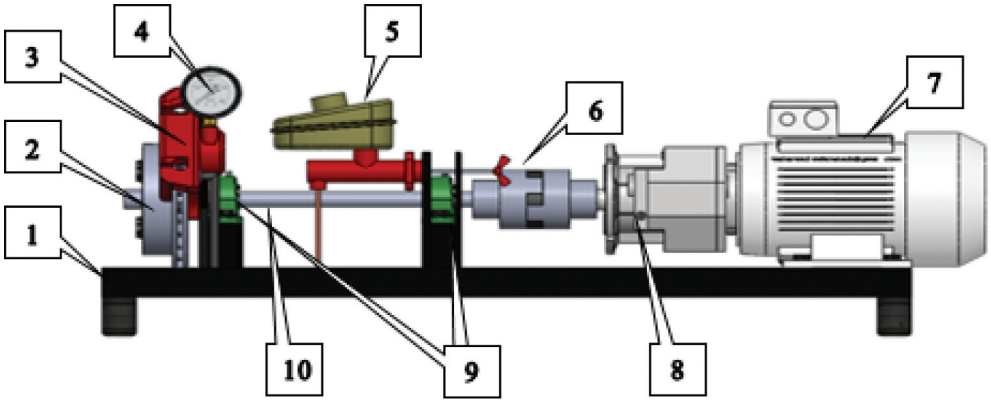


Figure 6. Machine used for experimental tests. 1) Structure, 2) Disc brake, 3) Brake caliper. 4) Pressure gauge, 5) Brake fluid reservoir, 6) Coupling 1, 7) Gear motor, 8) Coupling 2, 9) Bearing, and 10) Shaft. Source: Own elaboration.

The value of the rolling resistance coefficient can be taken as a constant value of 0.015 for private vehicles that circulate on a concrete or asphalt surface (García-León and Flórez-Solano 2017). In this way, the deceleration of the vehicle is calculated with Equation (4)

$$a_{M'ax} = \frac{W \times \mu}{\frac{W}{g}} = \mu \times g \tag{4}$$

Once the braking force is obtained, the force exerted on the pedal was calculated, with the following assumptions, the pedal torque increases the force exerted on the pedal by 4.5 times the initial force applied to the brake pedal, the servo brake increases 855 times the force coming out of the pedal-torque, and the master cylinder increases 5 times the force of the servo brake. The value of the pedal force will be the necessary force that the driver must apply to stop the vehicle, which is calculated with Equation (5):

$$F_{Pedal} = \frac{F_f}{F_P \times F_S \times F_C} \tag{5}$$

Equation (6) is used to calculate the peripheral speed, this value establishes the relationship between the linear speed of the vehicle and the peripheral speed of the tire, and thanks to this, the braking of the vehicles is generated. An adherence of 80% is assumed, and the variable is obtained V_P.

$$X = \frac{(V_i - V_P)}{V_P} \times 100 \tag{6}$$

The peripheral speed is the same for each disc brake, which is at the initial speed of 36 km/h (downtown mainly). The braking process is carried out thanks to the friction between the pads and the disc brake, transforming the kinetic energy of the vehicle into heat. To calculate this dissipated energy, it is necessary to know the vehicle mass equal to 1,650 kg, the correction factor i = 1.25 for rolling masses, and the vehicle speed at the moment of braking initiation 36 km/h, for this calculation, Equation (7) is used:

$$E_f = \frac{i \times m_v \times \left(V_i^2 - V_f^2\right)}{2} \tag{7}$$

Equation (8) is used to calculate the energy dissipated in the front of the disc brake; it is necessary to know that the total energy is distributed between 70% and 80% on the front axle because the most significant amount of mass of the vehicle is present on that axle.

$$E_{Frontaxle} = E_f \times 0.70 \tag{8}$$

Of the total energy absorbed in the front axle, 90% is dissipated in the disc brake and the remaining 10% in the pad. For this calculation, Equations (9) and (10), respectively, are considered. Since the shaft has two discs, the dissipated energy is distributed, and thus Equation (11) is used

$$E_{Disc} = E_{Rearaxle} \times 0.9 \tag{9}$$

$$E_{Pad} = E_{Frontaxle} \times 0.1 \tag{10}$$

$$E = \frac{E_{Disc}}{2} \tag{11}$$

The energy that the disc brake must dissipate is taken from Equation (11), and therefore it must be dissipated as quickly as possible to avoid overheating. This depends on the geometry of the disc brake, the material with which it is manufactured, and the operating conditions.

2.4. Friction force on the pads

To calculate the friction force between the disc and the pad, it is necessary to apply the adhesion factor between the road and the tire equal to 0.85 under dry road conditions (Stachowiak 2005). Equation (12) is used to determine the braking length; it is necessary to know the vehicle mass, the friction force, and the initial and final speed.

$$l = \frac{1}{2} \times \frac{m_v}{g \times F_r} \times \left(V_i{}^2 - V_f{}^2\right) \tag{12}$$

The braking time is the period necessary to evaluate whether the disc brake is optimal with its configuration and geometry, considering the distance and initial and final braking speed using Equation (13).

$$t = \frac{2 \times (x_f - x_i)}{(V_i - V_f)} \tag{13}$$

2.5. Disc brake thermal analysis

The kinetic and potential energy of the vehicle generates the power of the system, which is transformed into heat energy generated by the real operating conditions of the vehicle. For the braking system to function correctly, the heat generated must be evacuated as quickly as possible so that repetitive braking does not generate a high temperature; therefore, the efficiency and safety of the braking process do not reduce. In addition, the vehicle movement helps in the dissipation of the heat generated through the phenomenon of heat transfer by natural convection and radiation.

The physical and thermal properties of the material of the brake disc (nodular grey cast iron of laminar graphite) were obtained from Table A-3 of the book on heat transfer of Yunus A. Cengel. k=41 J/s×m×°C, C_p=434 J/Kg×°C, ρ=8131 Kg/m^3, α=11.6 ×10^6 m^2/s and U=32 J/s× m^2×°C (Cengel 2007). The rise in temperature of a brake assembly is mathematically governed by Equation (14), and the temperature on the surface of the disc is calculated using Equation (15)

$$\Delta T = \frac{E_{disco}}{m_D \times C_p} \quad (14)$$

$$T_i - T_\infty = \Delta T \quad (15)$$

The disc brake that is at a temperature Ti will cool by natural convection if it is left at room temperature according to the exponential Equation (16), known as Newton's cooling law:

$$T_i - T_\infty = (T_i - T_\infty) \times e^{-\frac{A \times U}{m \times C_p} \times t} \quad (16)$$

Since the disc brake contacts the pads via two surfaces, the contact surface area is calculated by Equation (17), taking into account the dimensions of the disc brake, and Figure 5 is used.

$$A_{contact} = 2 \times \pi \times \left(r_{ext}^2 - r_{int}^2\right) \quad (17)$$

3. Results and discussions

3.1. Thermal behaviour of the disc brake as a function of brake pads

Table 2 summarised the mathematical results obtained for the disc brake shown in Figure 5. The calculations were developed considering the heat transfer theories and each of the proposed Equations (1)–(17). The mathematical results indicate that a vehicle with a mass of 1,650 kg and that has a speed of 36 km/h, circulating in an environment of 25°C, with a friction surface between the disc and the pad, the temperature that is generated on the brake disc until it stops is approximately 74.24°C, obtaining results similar to those found by Topouris et al. (2019) and Lakkam et al. (2013).

The experimental results obtained for the disc brake under different operating conditions are summarised in Table 3. As was observed, a significant dependence of the brake pad type is evident for the different experimental conditions evaluated. The temperature on the brake pad was influenced by the pressure applied during the braking process, which was greater for condition C2 when was applied pressure of 45 PSI, the pressure exerted between the disc brake and the pad during the motion to generate the reduction of speed of the vehicle. Notice that for this case, a wear thickness by the friction action promoted a reduction of around 0.0178 μm on the disc brake when the Ti is around 77°C and 73°C for the disc brake and pad, respectively. For similar conditions, C1 with less contact pressure (35 PSI) reduces the temperature on the disc by around 20% related to condition C1. Still, the material removal during sliding is high, around ~2.5 times more of reduction on the wear thickness (disc wear) (0.0457 μm). Thus, it is evident the influence of the brake pad behaviour on the performance of the braking system and useful life of the disc related to the experimental conditions such as the contact pressure and the time during the braking process.

In conclusion, the C1 (asbestos) pads favour the performance on the disc brake in terms of less temperature generated on the disc. Still, the replacement and maintenance are ~2 times more than the condition C2 (semi-metallic) brake pad. However, the wear generated on the brake pad is mainly influenced by the hardness of the pad material. Likewise, greater removal of material from the disc generates a more significant increase in temperature as a function of the execution time of the braking process due to the friction coefficients generated, as was observed in both conditions C1 and C2.

Solving Equation (16) for Ti of Newton's cooling law, the cooling behaviour as a function of time is obtained, as shown in Table 4 and plotted in Figure 7. After having been subjected to a temperature of ~74.24°C during braking, the disc brake will take an ambient temperature of 25 ± 1.5°C when reaching approximately 15 min with a few variations on the temperature depending on the experimental condition related with the different brake pads. As was observed, the time of totally cooling is around 1,500 s equal to 25 min (25°C), as long as the cooling occurs by natural

Table 2. Mathematical results obtained for the disc brake.

Equation	Variable	Units	Mathematical Result
1	F_f	N, Kg	13,560.240 = 1,382.76
4	a_{Max}	m/s^2	8.33
5	F_{Pedal}	N	70.90
6	V_p	m/s	5.55
7	E_f	J	103,125.00
8	$E_{Front\ axle}$	J	72,187.50
9	E_{Disc}	J	64,968.75
10	E_{Pad}	J	7,218.75
11	E	J	32,484.37
12	I	m	6.08
13	t	s	1.22
14	ΔT	°C	49.24
15	Ti	°C	74.24
17	A	m^2	0.20

Source: Own elaboration.

Table 3. Experimental results.

Condition	Pressure [PSI – (N)]	Time (s)	Pad thickness (μm)			Pad temperature (°C)		Disc temperature (°C)
			Initial	Final	ΔPt	Initial	Final	
C1	**23 (15.85)**	60	14.1630	14.1275	0.0355	23.00	26.50	30.02
		90	14.1275	13.9852	0.1423	26.50	29.70	31.08
		120	13.9852	13.7770	0.2082	29.60	34.40	32.30
		150	13.7770	13.7439	0.0331	34.40	55.90	33.40
	28 (19.30)	180	13.7439	13.4976	0.2463	35.90	36.10	35.20
		210	13.4976	13.4645	0.0331	36.10	38.60	37.60
		240	13.4645	13.4468	0.0177	38.60	40.70	39.30
	35 (24.13)	270	13.4468	13.3807	0.0661	40.70	43.10	42.50
		300	13.3807	13.2994	0.0813	43.10	53.00	47.60
		330	13.2994	13.2537	0.0457	53.00	54.60	49.30
C2	**22 (16.15)**	60	14.6253	14.6152	0.0101	27.60	29.60	29.60
		90	14.6152	14.5821	0.0331	29.60	43.50	33.90
		120	14.5821	14.5644	0.0177	36.20	48.70	38.90
		160	14.5644	14.5466	0.0178	40.80	53.40	47.20
	30 (20.68)	60	14.5466	14.5085	0.0381	42.70	58.60	49.50
		90	14.5085	14.4932	0.0153	46.60	59.80	59.10
		160	14.4932	14.4831	0.0101	48.70	63.10	71.00
	45 (31.02)	60	14.4831	14.4755	0.0076	54.80	64.60	60.70
		90	14.4755	14.4602	0.0153	56.60	71.60	64.20
		160	14.4602	14.4424	0.0178	65.30	73.70	77.70

Source: Own elaboration.
Note: C1, asbestos, and C2, semi-metallic brake pads.

Table 4. Newton's cooling law calculations.

t (s)	Temperature (°C)						
	Mathematical	Experimental					
0	**74.24**	**33.40**	**39.30**	**49.30**	**47.20**	**71.00**	**77.70**
100	55.17	30.15	33.76	39.89	38.60	53.18	57.29
200	43.48	28.15	30.37	34.12	33.33	42.27	44.78
300	36.32	26.93	28.29	30.59	30.11	35.58	37.12
400	31.94	26.18	27.01	28.42	28.13	31.48	32.43
500	29.25	25.73	26.23	27.10	26.92	28.97	29.55
600	27.60	25.44	25.76	26.29	26.17	27.43	27.79
700	26.60	25.27	25.46	25.79	25.72	26.49	26.71
800	25.98	25.17	25.28	25.48	25.44	25.91	26.05
900	25.60	25.10	25.17	25.30	25.27	25.56	25.64
1000	25.37	25.06	25.11	25.18	25.17	25.34	25.39
1100	25.22	25.04	25.07	25.11	25.10	25.21	25.24
1200	25.14	25.02	25.04	25.07	25.06	25.13	25.15
1300	25.08	25.01	25.02	25.04	25.04	25.08	25.09
1400	25.05	25.01	25.02	25.03	25.02	25.05	25.06
1500	25.03	25.01	25.01	25.02	25.01	25.03	25.03

Source: Own elaboration.

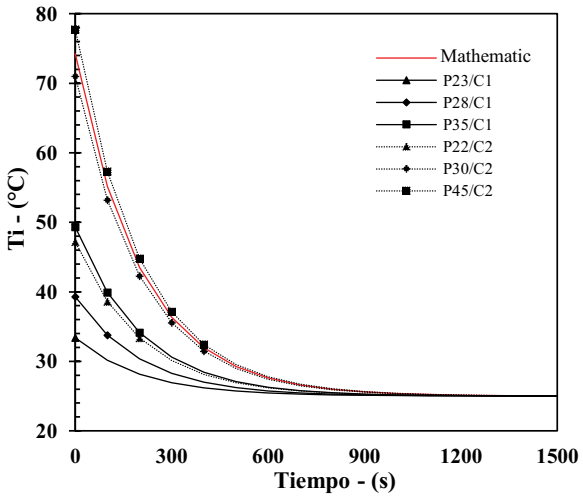


Figure 7. Behaviour of the Newton cooling. Source: Own elaboration.

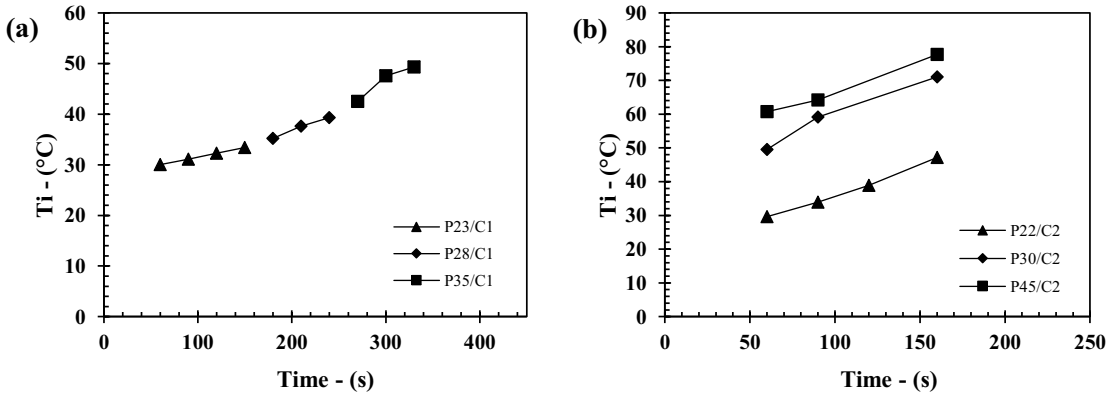


Figure 8. Influence of braking pressure as a function of temperature. (a) C1 y (b) C2. Source: Own elaboration.

convection, that is, that the air in the environment must have a velocity equal to 0 m/s (García-León, Flórez-Solano, and Acevedo-Peñaloza 2018; García-León, Echavez-Díaz, and Flórez-Solano 2018; Talati and Jalalifar 2009).

However, as was previously mentioned, P45/C2 is the condition that reaches the maximum temperature over the disc brake (77°C) due to the metallic coupling between the disc and brake pad that is not generated with the asbestos pad where the temperature is less, but the wear thickness is higher. In this way, P23/C1 is a condition that provides the minimum temperature on the disc brake around 33.4°C. Although, notice from Figure 7 that the Newton cooling law is related to the temperature and time for the disc to reach the ambient temperature, a long-term problem is that the microstructure of the disc brake can suffer modifications on its morphology that prejudice the hardness values and thus the wear can be increase. Also, cracks along the wear track of the disc can be generated because of the gradients of temperatures that are exposed in short times when the disc is cooling or exposed to the rain or puddles of water directly (García-León, Flórez-Solano, and Acevedo-Peñaloza 2018).

Figure 8 shows the results obtained experimentally, taking into account the different brake pads. The speed of the vehicle influence the kinetic energy that is generated during the movement because it does not affect linearly but increases its value exponentially (Belhocine and Bouchetara 2013c). This means that two vehicles of equal weight, one moving at twice the speed of the other, do not require double braking force to stop the vehicle but will require four times more; therefore, the stopping distance will be longer as long as it is on a flat road (García-León, Acevedo-Peñaloza, and Rojas-Suarez 2019; Cristol-Bulthé et al. 2008). On the other hand, the material of the brake pad influences the thermodynamic properties of the disc brake, causing an increase in temperature, as can be seen in Figure 8, this causes a longer time for heat dissipation to the environment and thus a reduction of the useful life of the braking system components (García-León 2017).

As was observed and commented, the C2 condition had the greater values of Ti due to the metallic coupling between tribosystem (pad and disc). Furthermore, notice that the C1 condition aid to the increasing of the temperature due to the braking process which is it exposed, this same behaviour can occur for the C2 condition behaviour, concluding that the performance of the coupling between the pad and disc brake differs considering the experimental parameters (temperature and cooling time) that could be evaluated, and thus provide a general visualisation of the behaviour of this important mechanical element for the automotive industry due to nowadays are few the experimental studies that consider the different variables in this type of systems.

4. Conclusions

In this study, experimental and mathematical results on an auto-ventilated disc brake with different brake pads have been investigated mainly in terms of heat transfer and cooling time. The main conclusions are summarised as follows:

- Bibliometric results indicated that in the *Scopus* database articles exists four clusters related to the study of disc brakes and thermodynamics, friction and wear, heat transfer and temperature, and the finite element methods. These areas were determined from 873 articles compiled from 1969 to 2021, which were published in 354 sources by 1,815 authors around the world, with an annual growth rate of 2.81%, showing that disc brake is an important subject to study concert to the automotive industry.
- A test machine was designed applying theories and methods of design, 100% functional was constructed to evaluate the contact surface

temperatures between the disc and the pad, and thus analyse the distribution of heat between two components (pad and disc brake) in sliding contact considering high-temperature gradients and the cooling times under different operating conditions which can affect the ventilation of the disc and thus the heat dissipation to the environment. The experimental data obtained from the machine designed were validated with mathematical calculations based on dynamic and heat transfer equations, which were in good agreement.

- The temperature on the pad and disc brake was influenced mainly by the pressure applied during the braking process. For the C2 condition (semi-metallic pad), the highest temperatures were observed to reduce the wear thickness of around 0.0178 μm on the disc brake when the Ti is around 77°C and 73°C for the disc brake and pad, respectively. In the same way, the C1 condition (asbestos) reduces the temperature over the disc brake surface by around 20% less, but the disc wear compared with the C2 condition is around 2.5 times higher. Notice that the increase in the temperature on the pad and disc brake (tribosystem) is also influenced by how the pilot executes the braking process. On the other hand, brake pad wear is influenced by the braking actuation time and the mechanical properties of the pad material.
- Finally, mathematical calculations allow corroborating the experimental behaviour of the data obtained. The heat generation and transfer calculations were carried out, considering the average speed allowed in urban zones of 36 km/h in the cities at an ambient temperature of 25°C. Therefore, if the researchers want to use higher speeds in their studies, the disc must be tested together with the manufacturing material, thus have a specific study to evaluate the behaviour of higher temperatures with other heat transfer types that can appear (Mechanical, physical and chemical properties of the material).

Nomenclature

A	Heat transfer area. (m^2).
a	Deceleration. (m/s^2).
a_{Max}	Maximum braking deceleration. (m/s^2).
C_P	Specific heat of the material. (J/Kg×°C).
E_{Disc}	Disc brake energy. (J).
E_f	Energy to dissipate by the braking system. (J)
$E_{Front\ axle}$	Front axle energy. (J).
E_{Pad}	Energy in the pad. (J).
F_C	Force in cylinder. (N).
F_f	Braking force. (N).
F_P	Torque force on pedal. (N).
F_{Pedal}	Pedal force. (N).
f_r	Rolling resistance coefficient. (0.01225 Dimensionless).
F_S	Force produced by the brake booster. (N).
g	Acceleration of gravity. (9.81 m/s^2).
k	Thermal conductivity. (J/s×m×°C).
m_D	Disc brake mass. (3.04 Kg).
m_v	Vehicle mass. (Kg).
Rr	Rolling resistance. (198.284 N).
t	Newton cooling time. (s).
T	Environment temperature. (22°C).
T_i	Instantaneous temperature at all times. (°C).
U	Coefficient of surface thermal transmission of the material. (J/s×m^2×°C).
V	Vehicle speed. (36 Km/h).
V_F	Final vehicle speed. (m/s).
V_i	Initial vehicle speed. (m/s).
V_P	Peripheral speed of the disc. (m/s).
W	Vehicle weight. (1,650 Kg=16,186.5 N).
X	Percentage of adherence. (%).
α	Thermal diffusivity. (m^2/s).
γ_F	Rotating mass coefficient. (Dimensionless).
μ	Coefficient of adhesion between tire and road. ($\mu=a_{Max}/g$ or 0.85 Dimensionless).
P	Material density. (Kg/m^3).

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Notes on contributors

R. A. García-León, received the BSc. in Mechanical Engineering from the Universidad Francisco de Paula Santander Ocaña, Colombia, in 2014, MSc. in Industrial Engineering of the Universidad de Pamplona, Colombia. He is Ph.D. in Scientist of Mechanical Engineering at InstitutoPolitecnico Nacional. He is linked since 2015 as a professor in the Department of Mechanical Engineering of the Faculty of Engineering of the Universidad Francisco de Paula Santander, Ocaña, Colombia. Researcher and coordinator of the research line Materials and Industrial Processes in the INGAP Research Group. Also, he is member of the Surface Engineering Group in Mexico. His areas of interest are mainly the development of mechanical systems, industrial processes, engineering materials, wear, and tribology.

G. Guerrero-Gómez, received the BSc. Mechanical Engineer from Universidad Francisco de Paula Santander, Specialist in University Teaching Practice from Universidad Francisco de Paula Santander Ocaña, Master in Advanced Energy Systems from Universidad de Santander. Full-time teacher since 2011 and Researcher of the GITYD group of the Faculty of Engineering at the Francisco de Paula Santander Ocaña University.

N. Afanador-García, received the BSc. Eng. in Civil Engineering and graduate in mathematics and Physic in 1990, the MSc degree Civil Engineering with an emphasis in structures at the Universidad of the Andes Colombia in

2008 and actually, he is PhD in Structures at the University of Brasilia. Since 2003 to actually, he works for Francisco of Paula Santander University Ocaña in civil engineering department.

ORCID

R. A. García-León http://orcid.org/0000-0002-2734-1425
G. Guerrero-Gómez http://orcid.org/0000-0002-4316-7113
N. Afanador-García http://orcid.org/0000-0001-5463-2036

Author contributions

R. A. García-León, Investigation, Supervision, Project administration, Conceptualization, Methodology, Formal analysis, original draft – preparation, writing – review & editing.

G. Guerrero-Gómez and **N. Afanador-García**, Investigation, Methodology, Formal analysis, other contribution.

Data availability

Data is openly available in a public repository that does not issue DOIs. The data that support the findings of this study are openly available in [Universidad Francisco de Paula Santander Ocaña repository] at [http://repositorio.ufpso.edu.co/handle/123456789/382], reference number [Thesis: 2246-2020].

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