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Thermal analysis of brake system components from low-lift vehicle

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Abstract. The objective of this work was to analyze the brake system of the prototype developed by UFV, using sensors and software as a source of obtaining of data. The low-profile off-road prototype must have a high working capacity on low-lift, sloping and irregular terrain, always complying with SAE Brazil's safety regulations and regulations. The methodology used was the determination of theoretical maximum temperatures and the characterization of thermal braking energies by experimental method. The presented results confirm that the pre-established conditions were actually met in order to promote the optimization of the related systems. It is concluded that the brake system used in the project meets the temperatures ranges considered safe for its good functioning.
Keywords: Energy. Comfort. Safety. Experiment.

Introduction

Braking system study, whether numerical or experimental, is important for the safety of the vehicle. Its purpose is to reduce or maintain a certain speed, as well as, to keep a vehicle stationary. These systems are devices that convert kinetic energy into thermal energy (or other energies) through friction. Thermal energies are not desirable and should be avoided as they may result in malfunction.

The brake systems used by the UFV Baja team are the disc brake. Talati and Jalalifar (2009) reported that the disc brake is used in light vehicles, whose advantage is the performance. These authors observed that long repetitive braking resulted in increased temperature of various brake components of the vehicle, which reduced the performance of the brake system. In order to reduce the effect of temperature on the disc brake, Bohl & Kurt (2007), Mutlu et al (2005), Mosleh et al (2004) study the thermal response of disc brake systems for different materials used for disc-pastille.

In this system, a steel disc is coupled to the wheel so as to accompany the rotation of the wheel forming assembly. When braking occurs, forceps press two pads against the disc, forcing an instantaneous reduction of the rotation of the disc through the friction generated between the materials.

The friction between the materials generates energy in the form of heat. Such energy is undesirable, since it can cause problems in the brake system such as fatigue and thermal cracking, heating of the brake fluid, reduction of the thermal wear resistance. Therefore, in order to increase thermal energy dissipation, it is common to use vented disks. These have holes or fins that allow air to enter, thus helping to cool it. This concern with the aerodynamic cooling of the brake system is studied by several authors (Johnson et al., 2003, McPhee and Johnson 2007, Wallis et al., 2002).

Another evidence, with regard to the generation of heat due to the friction of contact, causing wear of the brake system was also studied by Yevtushenko and Chapovska, (1997) and Ostermeyer (2001).

It is necessary to predict the temperature rise of a given brake system and to evaluate its thermal performance in the initial stage of the project. It was found from Lee (1999) and Valvano & Lee (2000) that vaporization of brake fluids can be a cause of some collisions. In this sense, proper inspection was recommended.

Thermal analysis in a brake system is employed in order to determine all the brake actuating temperatures as well as the heat transfers generated along the material. Thermal analysis provides a better understanding of the friction heat rates and how each component of the brake system behaves when receiving this amount of heat generated. Thus, there is a better control over the heating of the system, predicting and avoiding problems like thermal cracks or change in the properties of the brake fluid by its heating.

Due to the importance of the thermal analysis in disc brake, several researches deepen the knowledge in this analysis. As an example, Gao and Lin (2002) worked with an analytical model to characterize the contact temperature distribution on the working surface of a brake. Another model analyzed was the macro-structural one presented by Dufrénoy (2004). This model studied the thermomechanical behavior of the disc brake, analyzing the real three-dimensional geometry of the disc-insert pair. Contact surface variations, distortions and wear were considered.

The hypothesis that precedes this work is that by knowing the thermal energies generated by braking it is possible to design the safest and most accurate form. In this way, this work proposes a thermal analysis of the brake system of the prototype developed by the UFV. With the data it will be possible to determine the actuating temperatures in the brake discs and brake pads, thus, to analyze whether the system as a whole is affected by this energy or not. Also, the objective was to propose the creation of a new methodology to obtain temperature data generated by the friction of the brake components. In this way the UFVbaja team can use this method for new experiments and perfect it to achieve better precision of the results.

Methods

The experiment was divided into two stages: the first determined the maximum theoretical temperatures and the second determined the thermal braking energies by experimental method.

For the case of the determination of the theoretical heating, the studies of heat generation in the braking proposed by Limpert (1999) were used. The author has developed a methodology for analysis of urban car brakes with a good approximation.

For the determination of actual heating in the brake region, two types of sensors were used to gauge the temperatures of the disc and the brake pads separately.

Among the equipment used is the infrared thermometer, which is an equipment that obtains the temperature of a certain object through the infrared radiation released. The equipment is able to select the maximum temperature found from a fixed number of measurements. For the experiment, the thermometer of the Instrutherm TI-920 was used. Thermocouples were also used, which are one of the simplest types of temperature sensors available. Compounded by two distinct metals joined at one end, when there is a difference in the temperatures of the end attached to the free end, an electrical potential difference proportional to the variation of that temperature arises (Seeback effect). Thus, there are several types of thermocouples, each with different metals and ranges of different applications. Due to the limited material resources, type K thermocouples were used. In addition to operating in a desired range, it has a high sensitivity, allowing a minimum value of 0.25° C, sufficient for the accuracy of the experiment.

The Arduino was used to receive the data acquired by the thermocouple and processed them showing the results in degree celsius in real time in a computer. Arduino is a free and single-board hardware with an 8-bit Atmel microcontroller, capable of performing control tasks and integrating circuits, both analog and digital. It is characterized by being small, lightweight, easy to install and have free code which was very useful for its configuration.

Shields are small hardware that can be plugged into the Arduino, which contains proprietary circuits where they perform a certain function. As the range of electric potential that appears in the thermocouples is very small, in the range of μV, it is necessary an amplification of its signal besides compensating the cold joint, which is important for a good gauging. The shield MAX6675 is a hardware capable of doing all this in a practical way, being this one chosen for the development of the study.

In the experimental procedure for the positioning of the thermocouple in the brake pad, a through hole was drilled with a 5mm bit close to the center of the abrasive part of the insert. Then a 6mm hole through the back of the metal, taking care not to go completely, leaving about 2mm of insert. Then, a nut was welded to the metal part so as to leave the holes concentric so as to be able to fix the tip of the thermocouple, as shown in fig. 1 and 2.

Figure 1 – Attaching the thermocouple to the insert.

Source: The author.

The insert was mounted on the front brake caliper, where higher braking power was expected due to load transfer, as shown in figure 3.

After the installation, the thermocouple was installed in the Arduino through the MAX6675, whose code gives us a temperature reading every 0.3 seconds. The Arduino was configured to send the temperature data via serial communication that was received by a notebook through the Hercules Setup Utility software.

Figure 2 – Thermocouple attached to the brake pad.

Source: The author.

After the configuration, the test was started in three stages. In the first stage the vehicle descended a hill of beaten earth in maximum speed, in a rise of 24 meters braking completely when crossing a specific point. The temperature data on the insert was then saved by the thermocouple and the temperature of the brake disk by the infrared thermometer.

In the second stage the vehicle lowered the same elevation of 24 meters, but doing 7 intermittent braking along the route, being in the last collected the data of temperature in the disk and the pellets.

In the third stage the vehicle went down completely, about 64 meters, with partial braking, that is, with friction between the pellet and the disc without the complete stop of the vehicle. After the end of the descent, the temperature data were collected by the thermocouple and the thermometer.

Figure 3 - Mounting the caliper with the thermocouple in the vehicle.

Fonte: O autor.

Results and discussion

From the properties of the materials of the components and the general information of the vehicle, shown in table 1, it was possible to find the maximum temperature at which the disk would arrive, taking into account the part of energy absorbed by it during braking.

Table 1 – Vehicle data for theoretical analysis.

Bulk	282 kg
Height of descent	24 m
k brake disc	51,9 W/mK
ρ brake disc	7870 kg/m³
c brake disc	486 J/kgK
Braking time	3 s
Maximum speed	16,66 m/s
Room temperature	21°C
k brake pad	181,6 W/mK
ρ brake pad	2765 kg/m³
c brake pad	837,3 J/kgK
Initial temperature	40°C

Fonte: O autor.

In this way, the maximum braking energy, E_f, was found in a single stop and the amount absorbed by the disk γ, defined by Limpert (1999), according to eq. 1 and 2:

$$E_f = mgh + \left(\frac{km}{2}\right)(V_1^2 - V_2^2) = 1.0548 \times 10^5\, J \qquad (1)$$

Where m is the mass of the vehicle, g acceleration of gravity, h is the height difference from position 1 to position 2, k is the correction factor of the rotating parts, (k ≈ 1+ I / R²m), where R the tire radius, V_1^2 and V_2^2, respectively, the speed at the beginning and at the end of the braking.

Eq. 2 was conveniently expressed in terms of the properties of the material.

$$\gamma = \frac{q''_D}{q''_D + q''_P} = \frac{1}{1 + \left(\frac{\rho_P c_P k_P}{\rho_D c_D k_D}\right)^{\frac{1}{2}}} = 0.4073 \qquad (2)$$

Where q''_D and q''_P represents respectively the heat rate entering the disk and the brake pad, $\rho_P c_P k_P$ and $\rho_D c_D k_D$ represents the specific mass, the specific heat, the thermal conductivity respectively for the insert and the break disk.

From eq.2, the energy absorbed by the disk, and transformed into heat during braking will be a maximum of 4.293 X 10^4 J.

According to Eq. 3, defined in Limpert, (1999) the maximum temperature reached by the disk was found, $T_{max,L}$, disregarding convection losses.

$$T_{max,L} = \left(\frac{5}{18}\right)^{\frac{1}{2}} \frac{q''_0 (t_s)^{\frac{1}{2}}}{(\rho c k)^{\frac{1}{2}}} + T_i = 42.78°C \qquad (3)$$

Where q''_0 is the rate of heat entering the disc immediately after applying the brake, t_s is the time to stop the vehicle and T_i is the initial temperature of the brake disc.

Eq.3 was considered for a braking time equal to the vehicle's standstill time divided by 2. In this equation it is evidenced that for a specified heat flux and braking time, the disc temperature will decrease to higher values of density, specific heat and thermal conductivity. Decreasing the heat flow by increasing the area of the brake sweep will also decrease the maximum surface temperature.

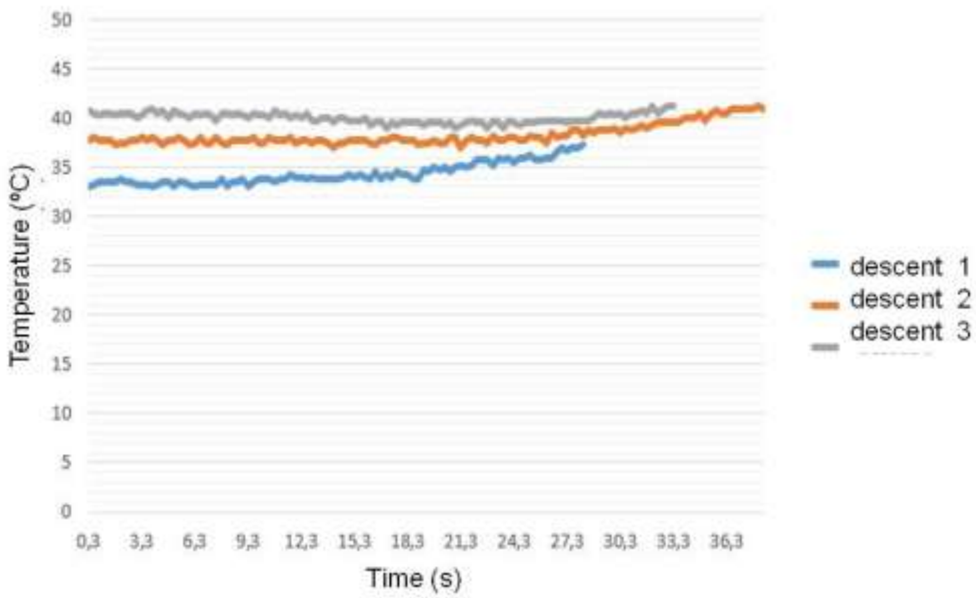
In the first part of the experiment, the infrared thermometer recorded a brake disc temperature of 40.2 ° C on the first attempt, 45.7 ° C on the second attempt and 46.4 ° C on the third attempt. For the pellet there was no significant temperature increase. These values obtained experimentally are in agreement with the value obtained in eq.3. By averaging these temperatures and comparing them with eq.3, there is a temperature difference of only 3%.

For the second part of the experiment, the calculations became imprecise due to the need to obtain values such as the coefficient of heat transfer by convection of the disk, which involves a variety of variables that must be obtained experimentally. In this way, it was decided to use the experimental data for the analysis. Thus, after the descent with 7 brakes, the final temperature of 54.6 ° C was reached on the first attempt, 102 ° C on the second attempt and 115.8 ° C on the third attempt. For the pellet, the temperature values along the braking in figure 4 were observed.

For the third part of the experiment, brake disc temperatures were 386 ° C, 395.2 ° C and 406 ° C at the first, second and third attempts, respectively. The brake pad temperatures were expressed in Figure 5.

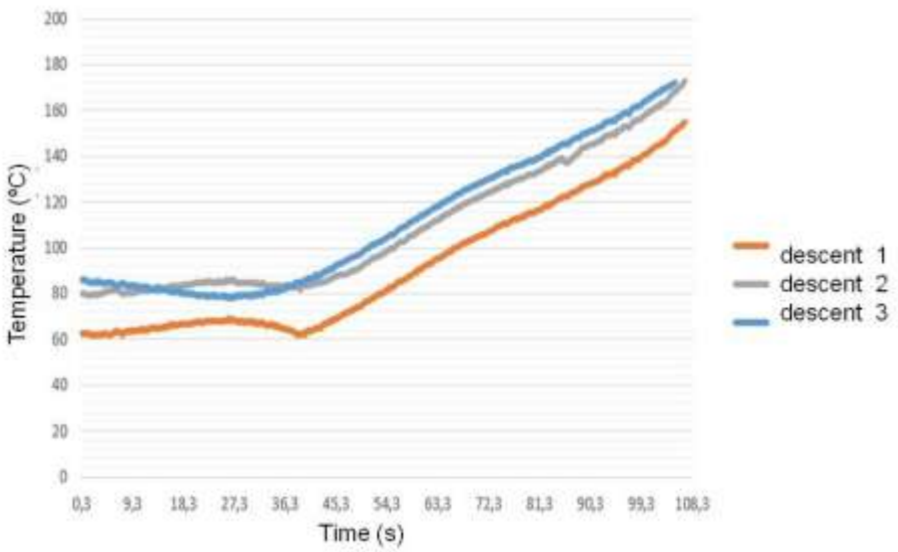
It is noted that the brake pad only reached high temperatures when constant braking is maintained, which consequently maintains a constant friction with the disc. In short-term braking, although the disc reaches temperatures close to 100° C, the tablet does not undergo large variations. The pellet-clamp assembly is responsible for the heating of the brake fluid through thermal conduction, we can conclude that only in extreme situations, such as the third stage of the experiment, problems of vaporization of the fluid can occur due to the high temperatures generated, since that for the DOT 4 fluid used in the system the dry boiling temperature is about 230ºC and about 160ºC for wet fluid.

Figure 4 - Descent with intermittent braking.



Source: The author.

Figure 5- Descent with partial braking.



Source: The author

Conclusion

Considering the theoretical analysis and the experimental tests carried out, the objectives of this work were achieved.

In competitions baja, for which the vehicle is built, the brakes are commonly used for the speed control in curves and obstacles, in addition to the safety and preservation of the rider in emergency situations. Therefore, the acceleration of the vehicle is more requested than the moments of braking during the tests. Given the conditions of the experiment of this work, it is concluded that the current brake system meets the ranges of temperatures considered safe for its proper functioning.

Still, it can be concluded that in baja competitions are situations of friction between disc and tablet for a long period of time. In this way, the system offers safety as long as the components are in good condition, new brake pads, clean brake disc, new fluid and no moisture.

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