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INVESTIGATING THE INFLUENCE OF VANE SHAPE ON BRAKE THERMAL PERFORMANCE: A THERMAL ANALYSIS APPROACH

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Abstract: For any type of existing vehicle, one of the most important systems in its structure is the braking system. It is also the main safety element, which stops the vehicle by converting kinetic energy into heat. For constructive reasons and thermal efficiency, ventilated discs are the most widespread and used in industry, therefore, they will also be used in this scientific paper. Ventilated discs are often used to automobile application because of their higher heat dissipation. The purpose of this work is to create a thermally efficient design for ventilated brake discs by adopting two different designs from a constructive point of view. A special importance was also for the brake disc material, initially a semi–metallic material was chosen, being the most used for discs, later the ceramic material was also chosen, which has improved thermal properties. The design variant for the brake disc, to which the disc material and the thermal shield are added, lead to a significant improvement from a thermal point of view, which was also the main objective of this work. Ultimately, this study underscores the pivotal role of innovative design strategies and material selection in advancing the thermal efficiency of ventilated brake discs, thus contributing to the broader landscape of automotive safety and performance engineering.
Keywords: braking system, ventilated discs, thermal efficiency, material selection, automotive safety

1. INTRODUCTION

The mechanical energy produced by an automobile engine serves to counteract environmental forces, inertial forces, and other external factors affecting the vehicle's motion. To halt this motion, a force or system, known as the braking system is required [1]. Gorjan, L et al. note in their study that within the vehicle's braking system, the frictional force between the disc and brake pads induces deceleration or complete cessation of motion by converting kinetic and potential energy into thermal energy [2][3]. The resultant thermal heat flow raises the temperature of the disc and its components, prompting scrutiny by specialists to optimize braking efficiency.

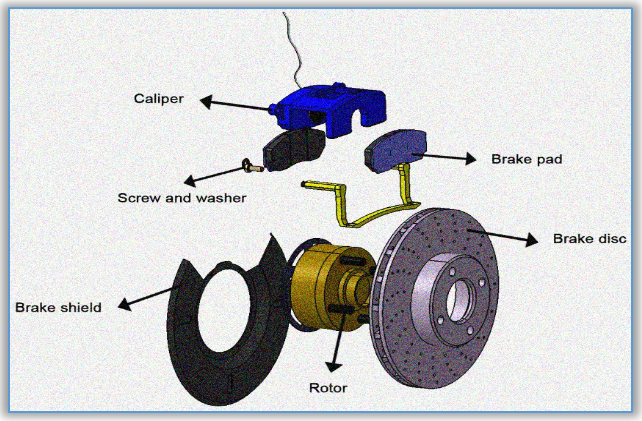


Figure 1. Main components for the braking system

The braking system serves as a primary safety feature in any vehicle, enabling drivers to effectively manage speed and come to a controlled stop when necessary. Whether navigating urban streets or traversing winding mountain roads, the ability to decelerate and stop safely is essential for preventing accidents and ensuring passenger safety. As such, the braking system must exhibit reliability, responsiveness, and consistency across various driving conditions and environments.

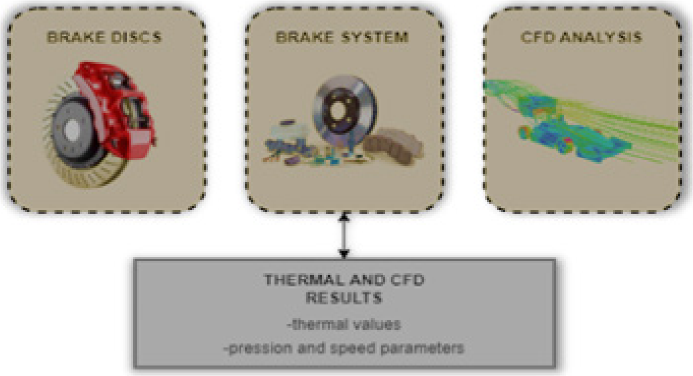


Figure 2. Research diagram–flow

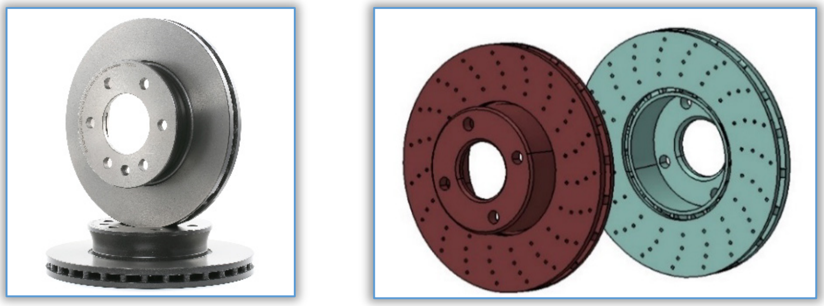
Efforts to mitigate thermal flow and temperature elevation on the disc's surface are closely tied to aerodynamics and disc design. Channels and perforated holes serve as crucial elements for efficient heat dissipation [4][5]. Figure 1 illustrates the principal components of the braking system. This study aims to devise a thermally efficient design for the brake disc, achieved through the implementation of internal ventilation channels, as presented in research diagram from Figure 2. Gulam and Salem underscore the importance of these channels in dissipating thermal flow from the disc's surface [4]. For contemporary high–performance vehicles, combating braking system overheating is a focal point of research due to potential issues such as reduced friction coefficient [6][7].

Among the key factors influencing brake disc cooling efficiency, the design and placement of ventilation slots stand out as crucial elements. These slots facilitate airflow across the disc surface, aiding in the dissipation of heat generated during braking. The effectiveness of ventilation slots in enhancing cooling performance has been widely studied and recognized in the automotive industry.

Regarding the ventilation channel design, it was positioned on both sides of the disc to facilitate comparison between the two placements. The temperature parameter served as the primary focus of design analysis to determine the thermal performance superiority between the variants [8]. Additionally, analysis of the braking system shield revealed its thermal functionality.

2. MODELS OF BRAKE DISCS AND THERMAL EVALUATION

The paper's analysis focused on developing two distinct brake disc designs, each approaching aerodynamics differently. Through thermal analysis, the study compared the temperature profiles on the disc surfaces of these two designs. Figure 3 illustrates these models in comparison to a commonly utilized ventilated disc in the automotive sector.



Conventional ventilated disc New concept for design of brake disc

Figure 3. Brake discs designs

To fabricate the brake discs, standard dimensions commonly employed in the automotive industry were utilized. The disc thickness was set at 22 mm, with an internal ventilation channel measuring 10 mm in thickness. Although the braking system assembly consists of numerous components, only the primary ones were constructed and assembled to streamline the analysis process. These system components were modeled using the CATIA V5 software and subsequently subjected to thermal analysis in ANSYS. Figure 4 depicts the geometric model representing the complete braking system.

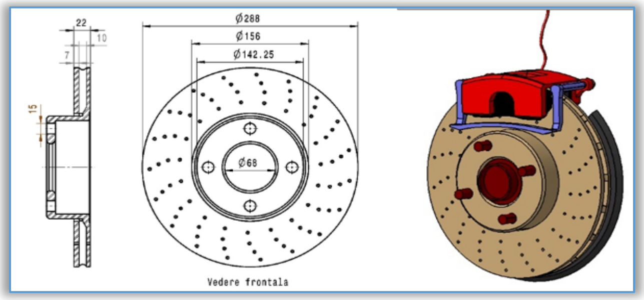


Figure 4. Geometric model for rear vent disc assembly and disc dimensions

In recent years, advancements in computational modeling and simulation techniques have provided valuable insights into the thermal behavior of brake discs and the influence of ventilation slots on cooling efficiency. Through detailed thermal analysis, researchers have gained a deeper understanding of the complex heat transfer phenomena occurring within the braking system.

The research centered on developing an enhanced iteration of the brake disc, prioritizing optimal heat dissipation [9]. Consequently, the study adhered to the following elements:

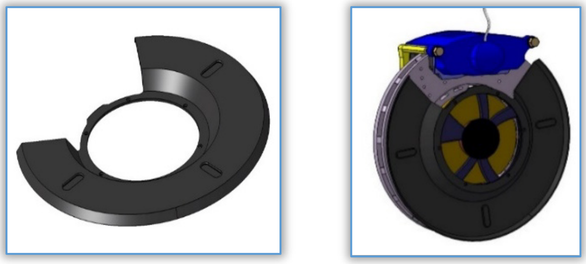


Figure 5. Thermal shield model

- Brake Disc: Two distinct constructive variations were crafted and evaluated, as depicted in Figures 6 and Figures 7.
- Thermal Shield: While commonly serving as a protective component in most vehicles, in this analysis, the thermal shield was exclusively considered for its thermal functionality.

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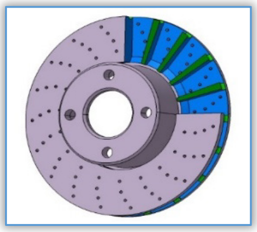
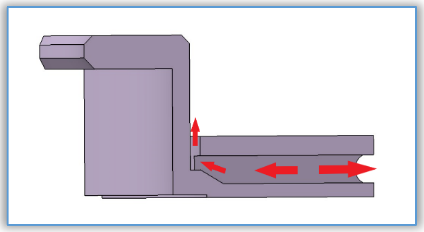


Isometric view for front duct ventilation

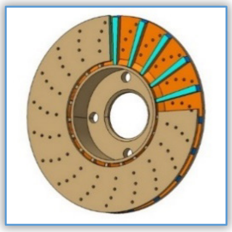


Section view for front duct ventilation

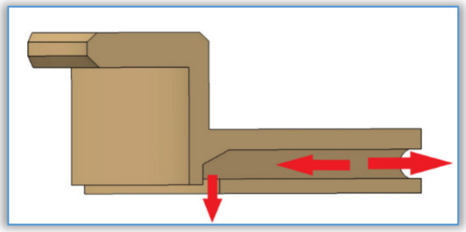
Figure 6. Front duct brake disc

Most car manufacturers incorporate brake shields nowadays, positioned inside the brake disc as depicted in Figure 5. Their primary function is safeguarding the brake disc and the entire braking system from debris and foreign objects that may accompany airflow beneath the vehicle during operation. Specifically, the brake shield's key role is shielding the brake disc from contaminants that could compromise its contact surface, leading to diminished braking efficiency. Additionally, from a cooling perspective, the brake shield acts as a barrier against convective heat transfer from airflow, helping prevent excessive overheating of the brake disc.

Ventilated shapes, commonly found in brake discs and pads, facilitate airflow through specially designed channels or vanes, allowing heat to be rapidly dispersed [10][11]. This prevents the buildup of excessive temperatures, which can lead to brake fading—a phenomenon characterized by reduced braking power and increased stopping distances. By promoting efficient heat dissipation, ventilated shapes help sustain optimal braking performance, ensuring shorter stopping distances, enhanced driver control, and improved overall safety on the road.



Isometric view for rear duct ventilation



Section view for rear duct ventilation

Figure 7. Rear duct brake disc

The choice between front and rear ventilation slot designs depends on various factors, including thermal management requirements, aerodynamics, and manufacturing considerations. Front ventilation slots offer direct cooling of the braking surface, making them suitable for applications where rapid heat dissipation is critical.

Additionally, both constructive iterations of the discs underwent analysis, with the most thermally efficient version selected for further testing using an alternative material: ceramic. Ceramic material offers enhanced thermal properties compared to its semi–metallic counterpart [12]. The material properties for the brake discs are outlined in Table 1 below.

Through ongoing research and development, FEA continues to play a critical role in advancing the design and material selection processes for automotive braking components.

Table 1. Thermo–physical properties for the materials used

Type of material	Thermal conductivity (W m−1C−1)	Density (kg m−3)	Specific heat (JKg−1 C−1)	Poisson ratio	Coefficient of linear expansion (K−1)	Young Modulus (GPa)
Semi metallic brake disc	60.5	7850	434	0.3	1.2 10−7	20
Ceramic brake disc	32	3750	786.6	0.27	2.6 10−6	24

Material selection plays a crucial role in the design and performance of brake discs, as they are subjected to high thermal and mechanical stresses during braking. The choice of material directly impacts the disc's ability to withstand heat, resist wear, and maintain dimensional stability under operating conditions.

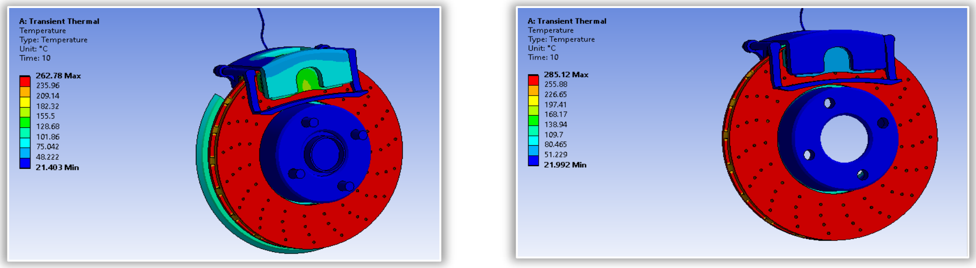
Through ongoing research and development, FEA continues to play a critical role in advancing the design and material selection processes for automotive braking components.

3. ANALYSIS FINDINGS

Analysis of semi–metallic material

Finite Element Analysis is instrumental in evaluating the performance of semi–metallic materials for brake discs. Through FEA simulations, engineers can assess the structural integrity, thermal behavior, and fatigue resistance of brake discs. Thermal Analysis allows researchers to model heat transfer within the brake disc and predict temperature distributions during braking. This information is crucial for assessing the disc's ability to dissipate heat effectively and avoid thermal degradation.

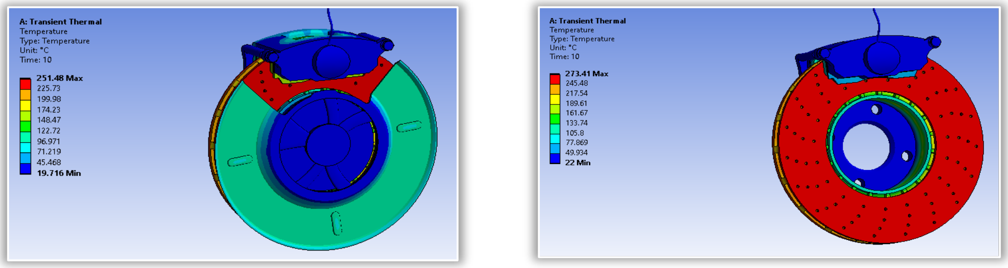
The thermal analysis outcomes are depicted in Figures 8 and 9 below, showcasing the disparities between the two models. With the inclusion of the thermal shield in the brake assembly system, a lower temperature was achieved, with a maximum temperature of 262.78°C for the front vent disc compared to 285.12°C without the brake shield.



with thermal shield assembled without thermal shield assembled

Figure 8. Temperature results for front vent disc

In the case of the second constructive option, featuring a rear vent, a noticeable reduction in temperature values is apparent. Semi–metallic materials are commonly used in brake discs due to their excellent thermal conductivity, high–temperature resistance, and good friction characteristics. These materials typically consist of a mixture of metal powders, such as iron, copper, and graphite, along with various additives to enhance performance.



with thermal shield assembled without thermal shield assembled

Figure 9. Temperature results for front vent disc

The maximum temperature recorded on the disc surface with the brake shield was 251.48℃, as depicted in Figure 8, whereas the variant without the shield registered 273.41℃, illustrated in Figure 8. These results underscore the significant thermal impact of the ventilation channel design.

Ceramic material

The subsequent phase of the thermal analysis concentrated on evaluating the ceramic material, identified as the optimal choice in terms of thermal performance. This material was incorporated into the variant that yielded the most favorable temperature readings, specifically the one featuring rear ventilation.

Ceramic brake discs stand out for their excellent performance, owing to their high thermal coefficient resulting from the material's thermal properties. However, the higher cost associated with ceramic discs poses a disadvantage compared to semi–metallic discs. Figure 10 below illustrates the analysis findings for the ceramic brake disc.

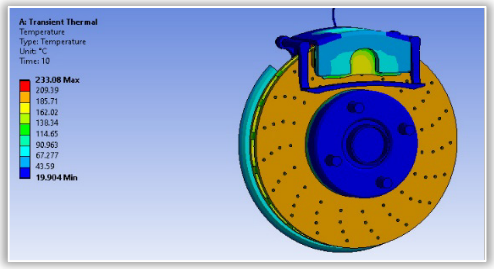


Figure 10. Thermal analysis for ceramic brake disc– rear vent

Upon altering the material, the thermal analysis revealed a decrease in temperature values for the specific case under consideration. The temperatures ranged from approximately 185 to 209℃.

CFD analysis results

The latter section of the paper centered on the Fluent Computational Fluid Dynamics (CFD) analysis, highlighting crucial parameters including static pressure, maximum and minimum speeds, all of which hold significance for the braking system [13]. In this section, it was discussed the application of CFD analysis for evaluating the aerodynamic performance of brake discs, with a focus on two key parameters: pressure distribution and airspeed.

An important input parameter for the CFD analysis was the air, so for that it was necessary to put the properties for it, as presented in Table 2 below.

Table 2. Properties for air

Material: Air	
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
Thermal expansion coefficient	0

The chamber configuration consists of a closed volume surrounding the brake disc, with an inlet wall and an outlet wall strategically positioned to promote airflow circulation. The inlet wall serves as the entry point for ambient air into the chamber, while the outlet wall facilitates the exit of heated air, creating a continuous flow pattern, presented in Figure 11. The design of the chamber aims to optimize airflow distribution and promote convective heat transfer from the brake disc to the surrounding air.

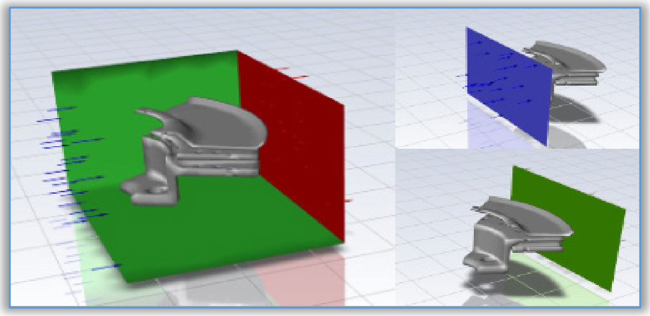
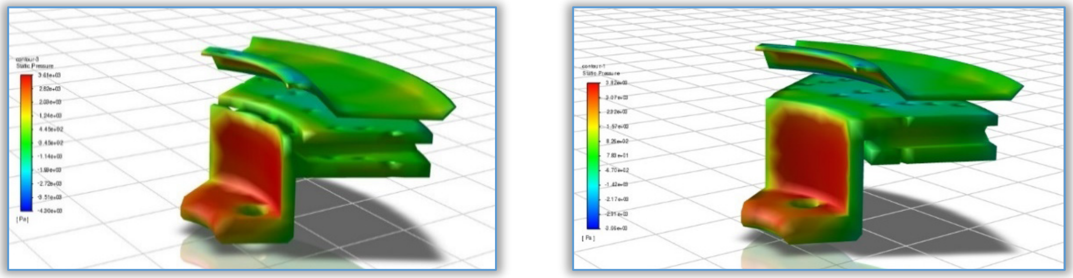


Figure 11. CFD analysis chamber for air flow

Figure 12 for the rear vent illustrates the static pressure distribution for the rear vent brake disc, while Figure 12 the front vent displays the static pressure distribution for the front vent brake disc.

Pressure distribution analysis involves examining how air pressure varies across the surface of the brake disc during operation. CFD simulations allow engineers to visualize and quantify pressure gradients, identifying areas of high and low pressure.



rear vent front vent

Figure 12. Static pressure for brake disc assembly

Airspeed analysis focuses on studying the velocity of airflow around the brake disc and through the ventilation slots. CFD simulations enable engineers to visualize airflow patterns and quantify airspeed profiles at various locations on the disc surface. Understanding airflow dynamics is essential for evaluating cooling effectiveness and heat dissipation rates.

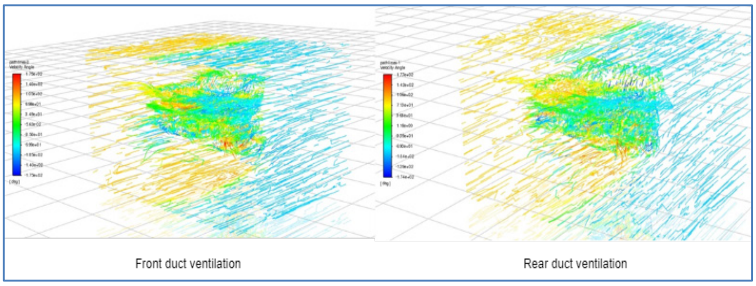


Figure 13. Speed parameter for brake disc assembly

The findings from the analysis reveal that the disc variant featuring rear ventilation demonstrates superior efficiency in terms of air circulation across the surface of the brake disc and shield assembly. This indicates that the rear vent design facilitates more effective airflow dynamics compared to alternative configurations. From the speed parameter analysis, in Figure 13 are presented the values for both variants, in which the assembly with front ventilation slot has a lower speed value.

CFD analysis offers valuable insights into the aerodynamic behaviour of brake discs, providing engineers with the tools to optimize design parameters and enhance performance. By analysing

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pressure distribution and airspeed profiles, researchers can develop brake disc configurations that maximize cooling effectiveness, minimize aerodynamic drag, and ensure reliable braking performance across a range of operating conditions.

4. CONCLUSIONS

Following the modeling of two distinct designs for the ventilation channel, a thermal analysis was conducted. The findings revealed that the geometric modifications have the potential to enhance the thermal efficiency of the disc.

In the Computational Fluid Dynamics (CFD) analysis, the parameter scrutinized, static air pressure, emerged as pivotal for the optimal operation of the system. Remarkably, the version of the disc featuring rear ventilation yielded superior outcomes, both thermally and in the CFD analysis.

Key conclusions drawn from the conducted analysis are as follows:

- Utilizing the thermal shield resulted in improved thermal performance.
- The constructive variant incorporating rear ventilation demonstrated lower thermal readings compared to its frontal counterpart.
- Upon comparing the two materials employed, the ceramic material showcased superior thermal properties, leading to lower temperature values.

The CFD analysis enables visualization and quantification of airflow circulation patterns within the chamber.

This research has provided valuable insights into the thermal analysis and aerodynamic performance of brake discs, highlighting the importance of design parameters for enhanced cooling efficiency and braking performance. Through a combination of finite element analysis (FEA) and computational fluid dynamics (CFD) simulations, it was possible to evaluate the influence of ventilation slot configurations, material properties, and chamber design on the thermal behavior and aerodynamic characteristics of brake discs.

NOMENCLATURE:

C	heat capacity (ρ Cp), Jm–3 K–1	T	temperature, K
Cp	specific heat, (J Kg –1K–1)	Tb	bulk temperature of the bath material, K
h	heat transfer coefficient, Wm–2 K–1	v	volume of the additive, m3
thermal conductivity,	Wm–1 K–1	GREEK LETTERS	
b	Semi thickness of plate	α	thermal diffusivity, m2 s–1
t	time, s	ρ	density,(Kgm–3)

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