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Analysis of the Influence of Brake Disc Material on Temperature Distribution Using Analytical and Numerical Methods

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Abstract
The objective of this study is to analyze the thermal behavior of a ventilated brake disc – a type commonly used in passenger vehicles due to its relatively effective heat dissipation to the environment. Although automotive braking systems have continuously improved and evolved over the past decades, the fundamental operating principle of braking remains unchanged. For this reason, researchers have always had a desire to find possible solutions to enhance braking efficiency. A moving vehicle is equipped with the braking system to control speed and come to a stop. The heat generated during braking is the result of repeated braking actions, where the vehicle's kinetic energy is converted into thermal energy. Brake components can become overheated, potentially leading to brake fade, which poses serious risks to both passengers and cargo. The heat generated during braking is mostly conducted into the disc and retained there, with most of this heat being released into the environment through forced convection. The main goal of this research is to analyze the thermal characteristics of a brake disc in dry contact with the brake pad during braking. The design and thermal analysis of the brake disc were carried out using ANSYS 2022 R1 software. This study also compares the temperature distribution in two different brake disc materials: FG15 and stainless steel.

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Keywords: Braking System, Braking Force, Braking Efficiency

1. Introduction

When a vehicle is in motion, the braking system is just as critical as any other component of the automobile. Over the past decades, automotive braking systems have undergone remarkable development—from mechanical friction brakes to drum brakes, and now to disc brakes, which are widely used today. The primary function of a vehicle's braking system is to reduce speed or bring the vehicle to a stop according to the driver's demand. The working principle of the braking system involves converting the vehicle's kinetic energy into thermal energy through friction generated at the contact surfaces during braking.

Currently, disc brakes are extensively used in automotive braking systems due to their advantages such as stable braking performance and effective heat dissipation. According to several studies, up to 90% of the heat generated during braking is absorbed by the brake disc [1, 2]. The high temperature of the brake disc leads to several negative consequences, such as increased wear, brake fade, and the formation of surface cracks. The rate at which kinetic energy is converted into thermal energy determines the braking power, while the braking efficiency depends on the cooling rate of the brake disc. If heat dissipation is slow, the disc temperature rises significantly, reducing braking effectiveness and possibly causing crack propagation.

The amount of work done during braking has a major influence on the amount of heat generated and is governed by several factors, including the pressure distribution at the contact surface. When modeling the braking system, two common assumptions are typically applied: (i) constant pressure distribution or (ii) constant wear rate of the friction material. These assumptions depend on the stiffness of the brake material, where harder materials tend to wear more evenly across the contact surface [3, 4].

The design and material selection of the braking system are critically important, as this is one of the most essential systems in vehicles. The primary requirement for brake discs is wear resistance. Wear or fracture occurs due to continuous contact under a certain pressure level. Stress may arise both from mechanical loads and thermal interaction. Therefore, temperature distribution across the disc should be considered from a system safety perspective. If the heat flux on the disc is non-uniform or certain areas reach excessively high temperatures, adjustments to the system should be made [5]. Previously, Do Van Quan *et al.* [11] studied the temperature distribution on three different materials: Grey Cast Iron, Inconel 718, and Inconel 625. The results showed that the maximum temperatures distributed on the brake disc were 94.693°C, 152.35°C, and 160.84°C, respectively, for a braking duration of 4 seconds. The authors concluded that Grey Cast Iron exhibited the lowest peak temperature distribution compared to the other materials. In addition to the studies, Ahmed *et al.* [8] used Autodesk Inventor 2019 software to design various 3D-shaped brake discs for the Bajaj Pulsar motorcycle and employed ANSYS to analyze factors affecting the disc, such as weight, stress, temperature, and deformation, to determine the optimal structure for improving brake disc quality before implementation. Chaturvedi *et al.* [9] conducted a temperature analysis of three types of materials by modeling with AutoCAD and simulating with ANSYS. other computational methods have been introduced and discussed in Refs. [9], [10].

Research on brake discs continues to attract significant global attention, aiming to improve their braking performance and durability. Although the materials used for brake discs are now highly diverse, it is essential to evaluate their safety factor before production. Therefore, this study focuses on analytically and numerically analyzing the temperature distribution corresponding to two types of materials—FG15 and stainless steel—using ANSYS 2022 R1.

2. Materials and methods

2.1 Brake Disc Materials

The brake disc is the most critical component in the automobile braking system in terms of vehicle safety and stability. The selection of brake disc material is based on various factors such as stability, frictional characteristics, wear resistance, and the ability to perform reliably under different conditions, including variations in speed, load, environment, temperature, and durability. Parameters to be considered when selecting a material include the coefficient of friction, wear resistance, density, and material cost.

The materials considered in this study are FG15 and stainless steel. The technical properties of these two materials are presented in the table below.

Table 1: Material Properties of FG15 and Stainless Steel

No.	Property	FG15	Stainless Steel
1	Thermal conductivity (W/m·K)	57	51
2	Density (kg/m³)	7250	7750
3	Specific heat capacity (J/kg·K)	460	480
4	Poisson's ratio	0.28	0.31
5	Young's modulus (GPa)	138	193
6	Coefficient of friction	0.35	0.40

2.2 Calculation of Input Parameters

To prevent collisions between vehicles, braking performance is given top priority. The heat flux on the brake disc model is calculated for a vehicle traveling at a speed of 33.33 m/s (equivalent to 120 km/h), and the calculation procedure is presented as follows: Vehicle mass (m): 1300 kg; Initial velocity (u): 33.33 m/s (equivalent to 120 km/h); Velocity after braking (v): 0 m/s; Brake disc diameter: 0.274 m; Load distribution on axle (γ): 0.42; Percentage of kinetic energy absorbed by the disc (k): 95% (i.e., 0.95); Gravitational acceleration (g): 9.81 m/s²; Coefficient of friction on dry road (μ): 0.7

(1) Energy generated during braking (K.E):

Formula:

$$KE = \frac{1}{2}.k.\gamma.m.(u-v)^2$$

Substituting the given values:

$$KE = \frac{1}{2}.0,95.0,42.1300.(33,33)^2 = 228109(J) \tag{2}$$

Braking Distance: x

Formula:

$$x = \frac{u^2}{2.\mu.g} = \frac{(33,33)^2}{2.0,7.9,81} = 80,9(m) \tag{3}$$

Deceleration Time (t)

Formula:

$$v = u + at \rightarrow t = \frac{v-u}{a}$$

Since the final velocity v=0, the braking time can be assumed directly as a given value: t=10 seconds

(4) Braking Power

Formula:

$$P_b = \frac{KE}{t} = \frac{398920,204}{10} = 28811(W) \tag{5}$$

Heat Flux Density

Brake pad contact area (A): 0.006 m²

$$Q = \frac{P_b}{A} = \frac{28811}{0,006} = 4801817(W/m^2)$$

Since the braking force distribution between the wheels is 61:39 (front: rear), the braking efficiency at the front wheels is 61%.

$$Q = 0,61 \times 4801817 = 2929108(W/m^2)$$

Table 2: Input Parameters for Thermal Calculation

Parameter	Value
Braking power (W)	28,811
Heat flux density (W/m²)	2,929,108
Convective heat transfer coefficient (Stainless Steel) (W/m²·K)	60
Convective heat transfer coefficient (FG15) (W/m²·K)	230
Ambient temperature (°C)	22

2.3 Brake Disc Model

The brake disc models were designed and analyzed under transient thermal conditions using ANSYS 2022 R1. The analysis was conducted over a 10-second interval, corresponding to the time required for the vehicle to decelerate from 120 km/h to a complete stop.

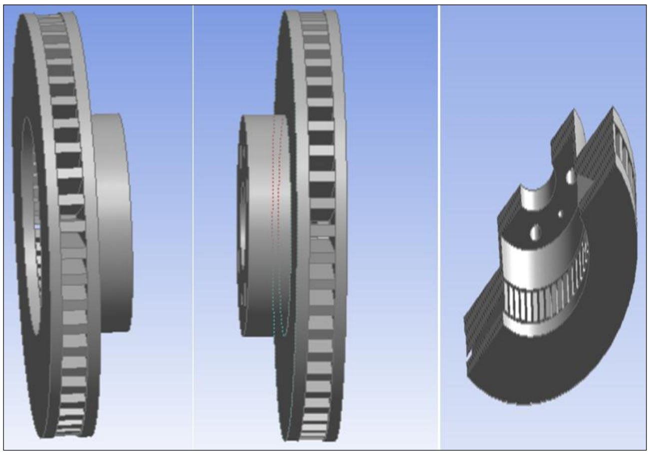

Fig 1:

3. Results and discussion

After performing the simulation using ANSYS software, the results are presented as follows:

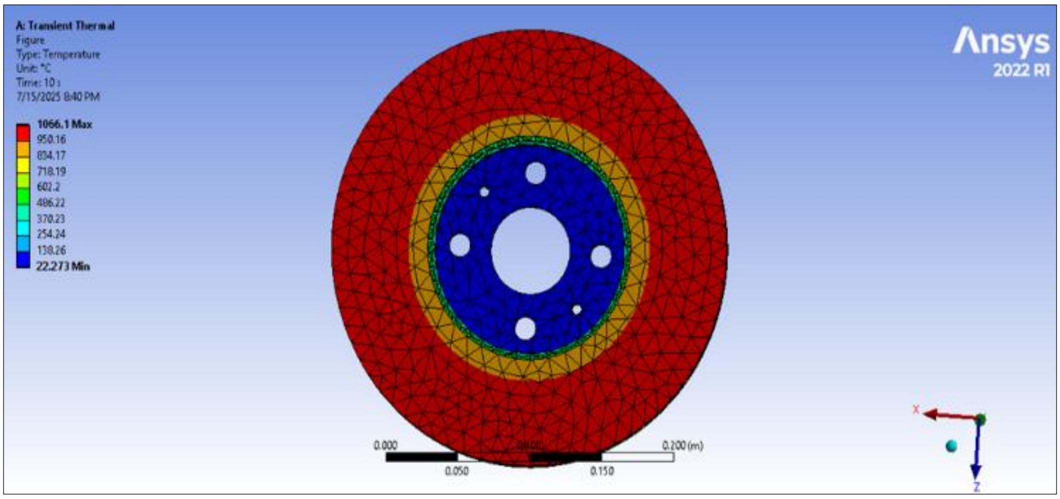

Fig 2: The results of the analysis on the brake disc made of gray cast iron FG15

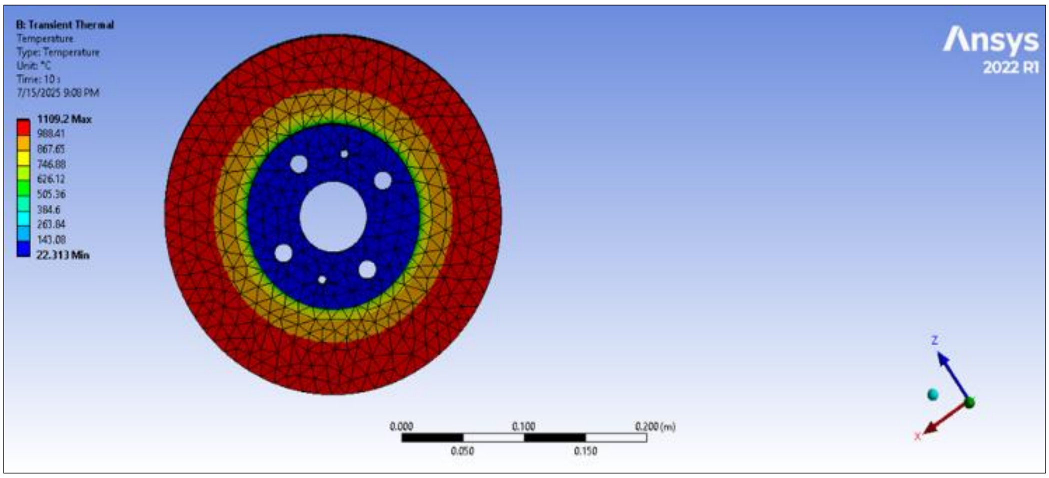

Fig 3: The results of the analysis on the brake disc made of stainless steel

The analysis results indicate that, under identical heat flux conditions applied to the disc surfaces, the maximum temperature observed in the FG15 brake disc is significantly lower than that in the Stainless-steel disc. This difference can be attributed to the inherent thermal properties of the two materials. As a result, FG15 is more thermally stable under the same braking conditions, making it a more suitable material in terms of thermal performance for ventilated brake disc applications.

4. Conclusion

In this study, the brake disc was analyzed to evaluate thermal spikes using both analytical calculations and finite element analysis (FEA). Under the same heat flux density, the amount of heat generated and retained in gray cast iron FG15 was found to be lower than in Stainless steel. Gray cast iron FG15 is a more suitable material for brake discs due to its superior thermal conductivity and ability to absorb thermal shocks. However, gray cast iron FG15 is more susceptible to corrosion under humid or rainy conditions.

Therefore, for road-going automobiles, Stainless steel can be considered a reasonable alternative thanks to its better corrosion resistance, even though its heat dissipation capability is inferior to that of gray cast iron FG15.

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