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Enhancing The Heat Dissipation Rate From Brake Disk Surface Through Improved Convection

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ABSTRACT : This research addresses a crucial need in automotive engineering by focusing on the thermal and structural analysis of disk brakes. The primary goal is to improve the heat dissipation rate from brake disk surfaces, addressing challenges associated with high-speed and repetitive braking. The study employs a comprehensive approach, conducting thermal and structural analyses to understand disk brake behavior under various conditions. It evaluates new materials for disk brakes based on thermal conductivity and mechanical properties and explores innovative design configurations for improved heat dissipation and structural integrity. The methodology involves designing six brake disc cases with different pocket configurations using CATIA. These designs are imported into ANSYS for simulation, where meshing and thermal analysis are performed. The findings highlight the effectiveness of Case 6, showing the highest temperature difference and maximum heat dissipation. Additionally, Case 6 with the maximum number of pockets demonstrates the lowest weight for the overall disk brake assembly, providing a vehicle weight advantage. In conclusion, the research contributes valuable insights to automotive engineering, offering a deeper understanding of thermal and structural aspects in disk brakes. The findings aim to enhance the development of reliable, efficient, and safe braking systems tailored to the evolving demands of modern vehicles.

***IndexTerms* - brake disk surfaces, CATIA, ANSYS, thermal and structural analyses.**

1. INTRODUCTION

Rotors, commonly referred to as brake discs, are integral components mounted to the hub of a vehicle, rotating with the wheel and tire. The hat, positioned at the center of the rotor, serves as the mounting point on the hub, and its center hub hole is precisely designed to fit the hub. During braking, substantial friction is generated as brake pads clamp against the rotor, slowing down the wheel and producing significant heat. Given the stresses of braking and the heat generated, brake rotors must exhibit strength and resilience to withstand high operating temperatures. Both mechanical and thermal stresses are inherent due to the combination of heating and mechanical loading during braking. Local overheating or hot spots can occur in brake discs, leading to structural changes, cracks, and damage that can shorten their lifespan. The predominant material for manufacturing brake rotors is cast iron, known for its affordability and effective resistance against fading. Two main types of rotors are employed: solid and vented.

Although the overall friction surface area is large, the contact area of the pads is relatively small. This design allows heat generation across the rotor's surfaces as pads are pressed against it. Most modern cars and trucks utilize vented rotors on the front brakes for enhanced cooling efficiency. Non-vented or solid rotors are commonly found on the rear of some vehicles and on the front of older or smaller vehicles where additional cooling is not as crucial. Efficient functioning of disc brakes necessitates rotor materials possessing specific properties, including a high, uniform, and stable coefficient of friction, inertness to environmental conditions, ability to withstand high temperatures (thermal stability), high wear resistance, flexibility, and conformability to any surface, good thermal conductivity, and heat absorption capacity. Additionally, high strength and durability are crucial to withstand torque loads, while effective vibration damping capacities minimize issues such as squeal and judder.

The dynamic or sliding coefficient of friction between the rotor and pads must remain stable for optimal braking efficiency. Different combinations of disc and pad materials yield varying coefficients of friction. Materials commonly used for rotors include Grey Cast Iron (GCI), Ductile Cast Iron (DCI), Martensitic Stainless Steel (MSS), and Aluminium Metal Matrix

Composite (ALMMC). It is noteworthy that various vehicles employ rotors with either straight passages or directional vents, with the latter enhancing airflow for improved heat dissipation but requiring correct installation orientation for optimal performance.
Brake pads are crucial components in the braking system of a vehicle, playing a pivotal role in converting kinetic energy into thermal energy to slow down or stop the vehicle. Their function is integral to the overall safety and performance of the braking system. In this comprehensive explanation, we will delve into the functioning and working mechanism of brake pads. The primary function of brake pads is to generate friction against the rotating brake disc or rotor, resulting in the conversion of kinetic energy into heat. This frictional force is essential for decelerating the vehicle and bringing it to a controlled stop. Brake pads are an integral part of disc brake systems, which are widely used in modern vehicles for their efficiency and effectiveness.

This study addresses a critical need in automotive engineering by focusing on the thermal and structural analysis of disk brakes. As a fundamental component for vehicle safety, disk brakes undergo significant thermal stresses during braking, impacting their structural integrity. With advancements in automotive technology and increasing demands for efficient braking, understanding and optimizing the thermal behavior of disk brakes have become imperative. The study responds to the challenges posed by high-speed braking and repetitive braking, aiming to prevent issues like brake fade, premature wear, thermal cracks, and disc thickness variation. By conducting a comprehensive analysis, the research contributes to the development of robust and high-performance disk brakes. It specifically targets advancements in material selection, design optimization, and innovative configurations to enhance heat dissipation and overall brake system efficiency.

2. LITERATURE SURVEY

In the realm of brake system research, various studies have contributed significantly to advancing our understanding of thermal dynamics, material behavior, and design considerations. (Jafari & Akyüz, 2021) [1] delved into the superiority of ventilated brake discs over solid ones, focusing on optimal design with radial vanes. Utilizing the Taguchi design of experiments, the study explored nine design parameters' impact on airflow and temperature distribution. Notably, the ventilation gap width emerged as a crucial factor, influencing brake disc cooling significantly.

(Pinca-Bretotean et al., 2021) [2] underscored the critical role of brake discs in efficient braking and heat dissipation. Employing CATIA V5 and ANSYS 19, the study conducted a computational thermo-mechanical analysis within a hydraulic brake system. The combination of numerical simulations and experimental evaluations emphasized the importance of understanding heat distribution for effective brake system design. (Jacob Moses et al., 2020) [3] focused on developing innovative brake pads by incorporating basalt fiber and glass fiber, aiming to replace conventional asbestos-based materials. The study's meticulous examination of various parameters demonstrated the superior properties of the newly formulated brake pads, particularly BB2, highlighting the potential of basalt and glass fibers as effective reinforcements.

(Zhang, Zhang, Wei, et al., 2020) [4] addressed the challenge of high temperatures faced by copper-based brake pads during emergency braking of high-speed trains. The study introduced a novel copper-based brake pad and investigated its tribological properties in the temperature range of 400–800 °C. The findings emphasized the importance of enhancing the oxidation resistance of graphite and the high-temperature strength of the copper matrix for designing high-performance copper-based brake pads. (Zhang, Zhang, Wu, et al., 2020) [5] investigated the braking performance of copper-based brake pads with varying carbon fiber content. The study highlighted the role of carbon fiber in enhancing wear resistance and stabilizing friction coefficients under demanding braking conditions. (Sri Karthikeyan et al., 2019) [6] explored advancements in brake technology, specifically addressing the environmental and health risks associated with the historical use of asbestos fiber in brake pads. The study introduced a novel brake pad material using natural fibers, providing an eco-friendly alternative and reducing health risks.
(Zhang et al., 2019a) [7] studied the fade behavior of copper-based brake pads during emergency braking, revealing insights into the formation of a friction layer composed of alternating copper-rich and iron-rich phases. (Modanloo & Talaee, 2018) [8] developed a thermal conduction model for advanced disk brakes in high-speed trains, providing accurate temperature profiles. The analytical solution demonstrated the model's ability to estimate temperature distribution in brake disks under various conditions. (Ahmed & Algarni, 2018) [9] analyzed the impact of design modifications incorporating radial grooves on disc brake performance. Direct Metal Laser Sintering was employed to introduce radial grooves, effectively managing temperature fluctuations under dynamic running conditions.

(Rudramoorthy et al., 2018) [10] focused on replacing traditional brake discs with lightweight materials to assess their performance under severe braking conditions in cars. The study compared materials like cast iron, steel, and Aluminum metal matrix composite, evaluating their stiffness, strength, and predicted stress and temperature distributions. (Hugar & Kadabadi, 2017) [11] presented a study focusing on the design and thermal analysis of disc brakes to minimize temperature. Different slot shapes on disc brake rotors for various vehicles were explored to optimize the thermal conductivity of the disc brake rotor. (Newase, 2017) [12] addressed structural and wear issues in two-wheeler brake systems, conducting steady-state thermal analysis to evaluate braking performance under various conditions. (Gupta et al., 2017) [13] conducted an in-depth analysis focusing on the crucial role of brakes as a major automotive component, emphasizing the need for continuous advancements to enhance road safety. (Abebe et al., 2016) [14] underscored the significance of meticulous design and material selection to prevent premature failure of the disc brake. The study involved analytical and finite element methods to study temperature and thermal stress distribution in the brake disc.

In summary, these studies collectively contribute to advancing brake system technology by addressing challenges related to heat dissipation, material performance, and design optimization. The varied approaches highlight the interdisciplinary nature of brake system research, integrating aspects of materials science, thermal analysis, and innovative design strategies.

3. METHODOLOGY

The study encompasses a comprehensive procedure to enhance the heat dissipation rate from brake discs through six distinct design cases created using CATIA. Subsequently, these designs are converted into .stp format and imported into the ANSYS design module for simulation. Meshing is applied to the imported designs, and thermal analysis is conducted with the temperature specified at the disk pad surface of contact. Material properties are meticulously applied to both the brake and the disc pad, followed by the application of boundary conditions on the disk brake. The culmination of this process involves the evaluation of thermal results utilizing the ANSYS Workbench, providing a holistic understanding of the heat dissipation capabilities of each design case

3.1. Design Of Disk Brake

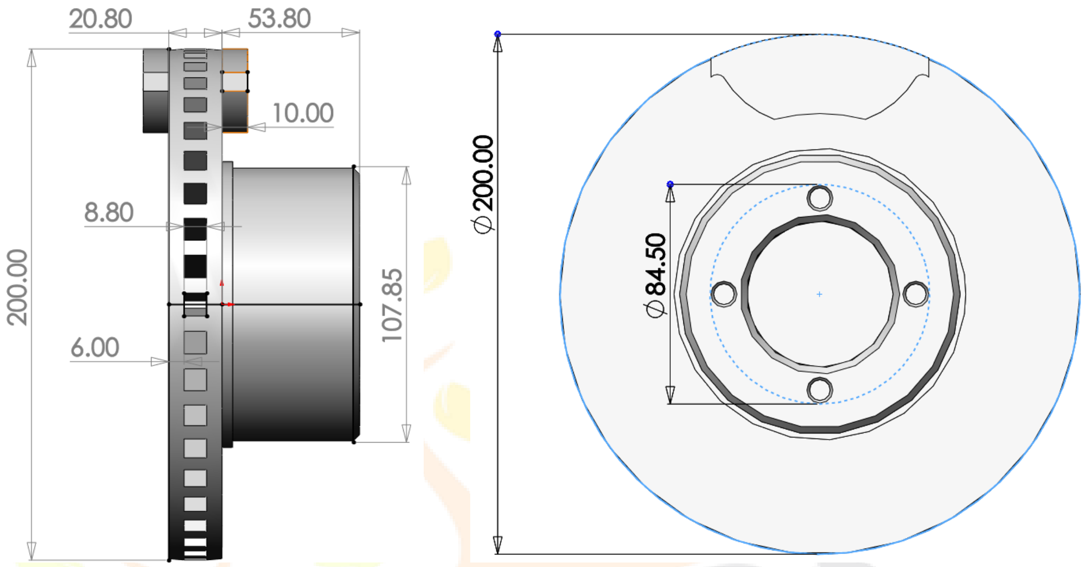

Figure -1 Design of Disk Brake

3.2. Mesh Generation

The technique of meshing involves breaking down an item's continuous geometric space into thousands or more different forms in order to accurately describe the physical shape of the thing in question. The 3D CAD model will be more precise and allow for higher fidelity simulations if the mesh is more dense. When a complicated geometry is divided into discrete components, it is called meshing. Mesh generation may be used to discretize a domain into two or three dimensions. Automated methods for meshing may offer quicker and more accurate solutions since meshing usually occupies a large part of the time it takes to get simulation results.

Table 1 Number Of Cases

CASES	TYPE
Case-1	Design Of Disk Brake With 10 Pockets
Case-2	Design Of Disk Brake With 15 Pockets
Case-3	Design Of Disk Brake With 20 Pockets
Case-4	Design Of Disk Brake With 25 Pockets
Case-5	Design Of Disk Brake With 30 Pockets
Case-6	Design Of Disk Brake With 35 Pockets

Table 2 Comparison Of Number Of Elements

CASES	NUMBER OF ELEMENTS
Case-1	55978
Case-2	59909
Case-3	84870
Case-4	85916
Case-5	85325

3.3. Boundary Conditions

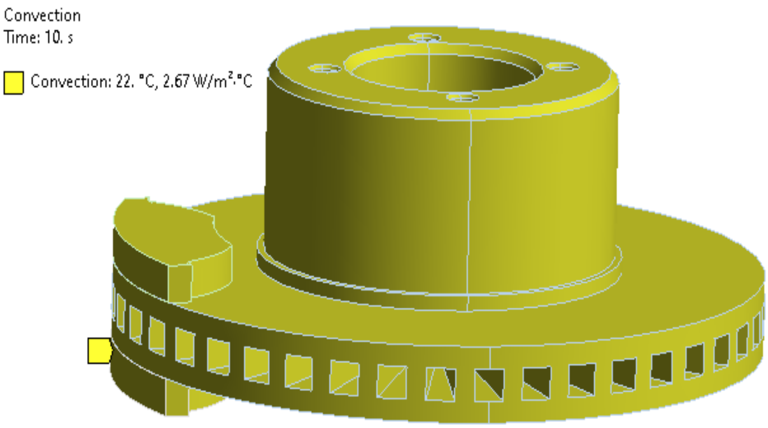

Figure -2 Convection Boundary Conditions

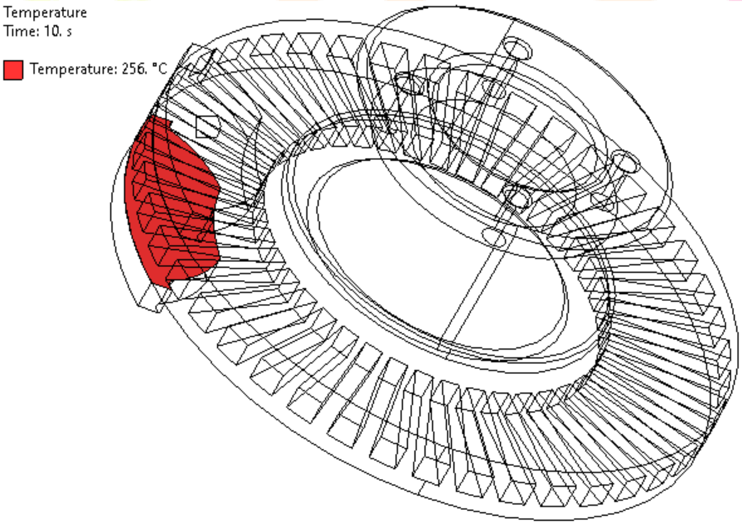

Figure -3 Temperature at the disk pad surface

In the ANSYS Workbench module, border conditions shall be applied by selecting the first mode of the simulation and specifying its physical properties. These parameters are the initial requirements for simulation. After fixing these parameters, the boundaries of each area are set and the following parameters are defined

- Total simulation period = 10 s.
- Convection Coefficient = 2.67 W/m^2 ^{o}C
- Temperature of the air film = 22^o C
- Temperature at the disk pad surface = 256^o C.
- Materials: For brake disk Grey Cast iron and semi-metallic/ceramic for the brake pads
- The Coefficient of friction = 0.3

4. RESULTS AND DISCUSSIONS

4.1. Validation Of FEA

The FEA of the base paper design as shown in figure 4 below has been used for the validation of the designed model, figure 5 as shown below.

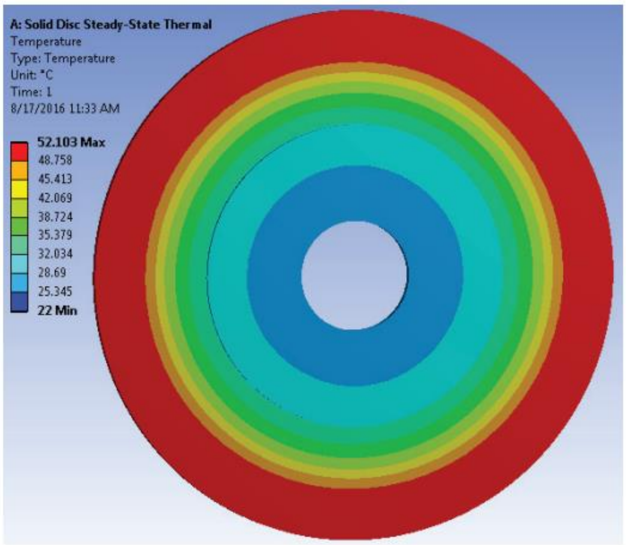

Figure 4 Base paper analysis results

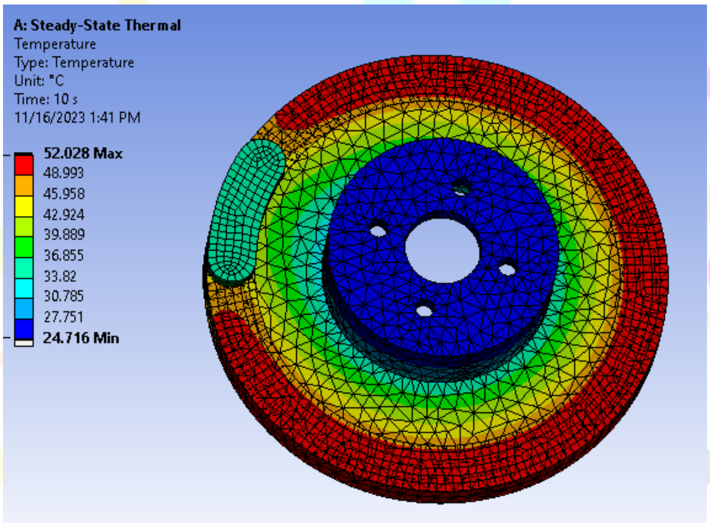

Figure 5 Validation of the model

4.2. TEMPERATURE DISTRIBUTION

4.2.1. Case-1 Design Of Disk Brake With 10 Pockets

In Figure 6, the brake disc's temperature analysis reveals a peak of 50.185°C near the pad contact region, reflecting intense friction during braking. Moving toward the center, temperatures gradually decrease, reaching a minimum of 23.894°C.

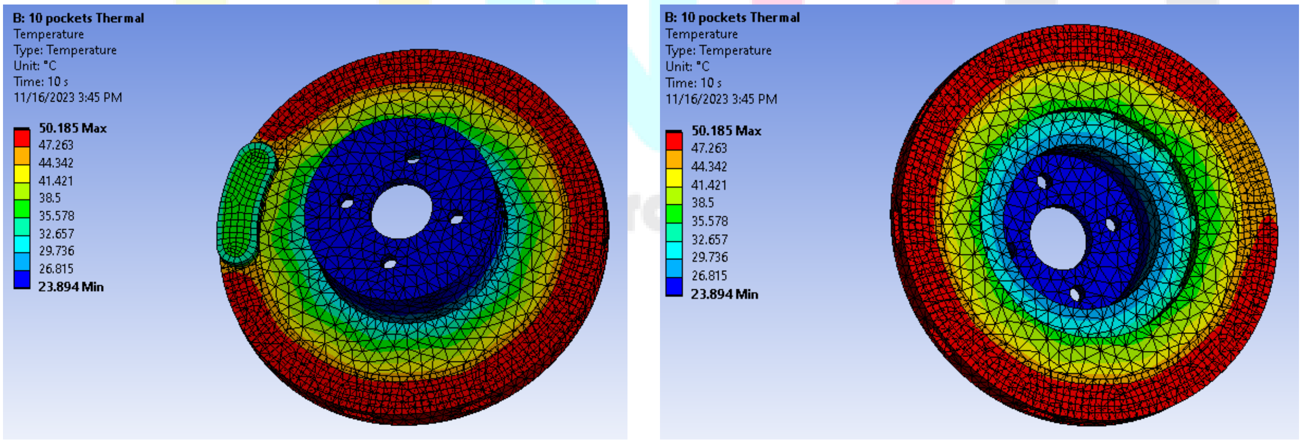

Figure 6 Case 1: Temperature Distribution

This thermal profile highlights localized heating near the contact point and effective heat dissipation towards the disc's center. Understanding these temperature variations is crucial for optimizing brake system designs, ensuring efficient heat management and overall performance under diverse braking conditions.

4.2.2. Case-2 Design Of Disk Brake With 15 Pockets

The temperature analysis reveals a peak of 49.042°C near the disk pad contact region as in figure 7, expected due to concentrated frictional heat. Moving towards the opposite end, a gradual temperature decrease is observed, reaching a minimum of 23.697°C. This decline is attributed to effective heat dissipation along the brake disc's length, resulting in lower temperatures at the distant end from the braking heat source.

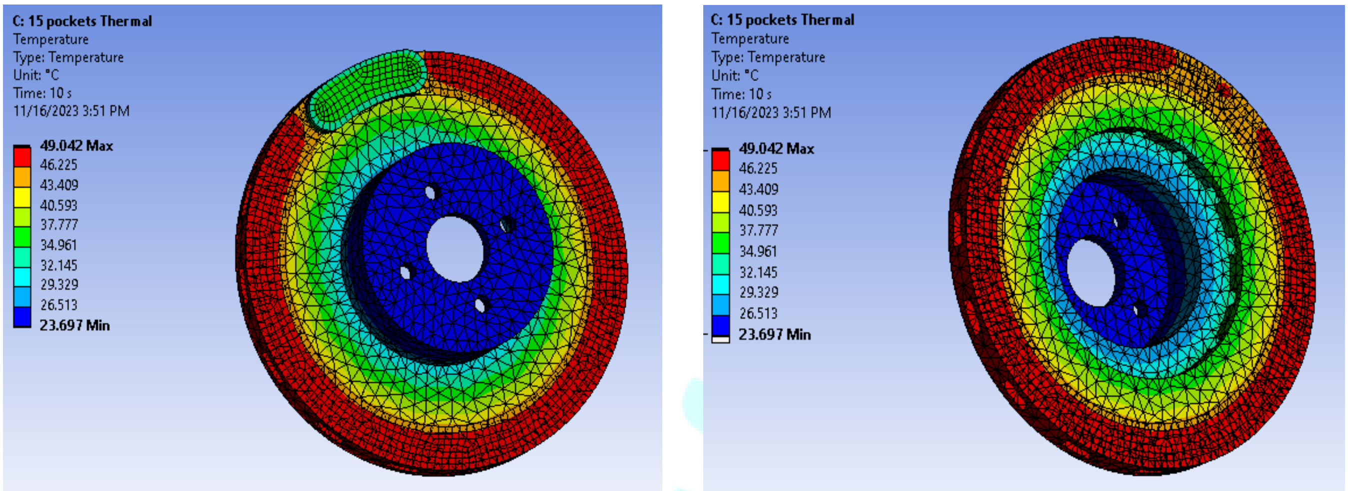

Figure 7 Case 2: Temperature Distribution

4.2.3. Case-3 Design Of Disk Brake With 20 Pockets

The temperature distribution analysis in Figure 8 provides insights into the brake disc's thermal behavior during operation. Notably, the temperature peaks at 48.094°C near the disk pad contact region, where maximum heat is generated during braking. This concentration of heat in the contact area is a crucial aspect of the brake system's thermal dynamics.

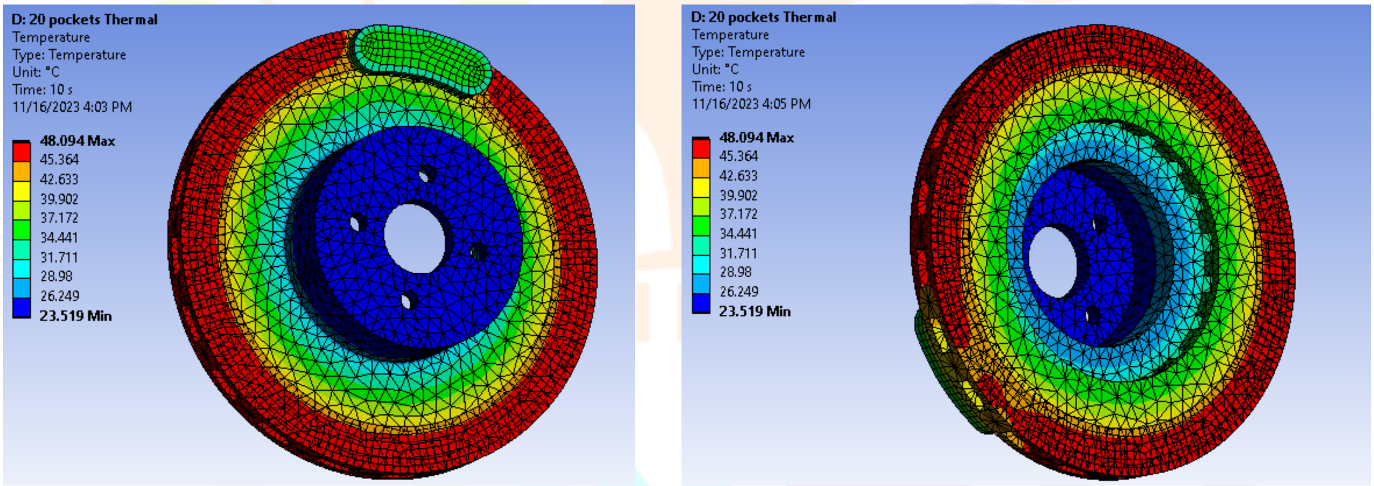

Figure 8 Case 3: Temperature Distribution

Moving towards the opposite end of the brake disc, a noticeable temperature decrease is observed. The recorded minimum temperature in this segment is 23.519°C. This decline is attributed to effective heat dissipation along the brake disc's length. The section farther from the contact region experiences lower temperatures due to enhanced heat dissipation mechanisms and increased distance from the primary heat source generated by braking.

4.2.4. Case-4 Design Of Disk Brake With 25 Pockets

In Figure 9, the temperature distribution analysis of the brake disc illustrates a peak temperature of 47.391°C in the vicinity of the pad contact area. Gradually decreasing towards the center, the temperature reaches a minimum of 23.353°C. This thermal pattern signifies localized heating near the contact surface during braking, with efficient dissipation leading to lower temperatures at the disc's central region. The understanding of such temperature variations is essential for optimizing brake system designs, ensuring effective heat dissipation, and overall performance across diverse braking scenarios.

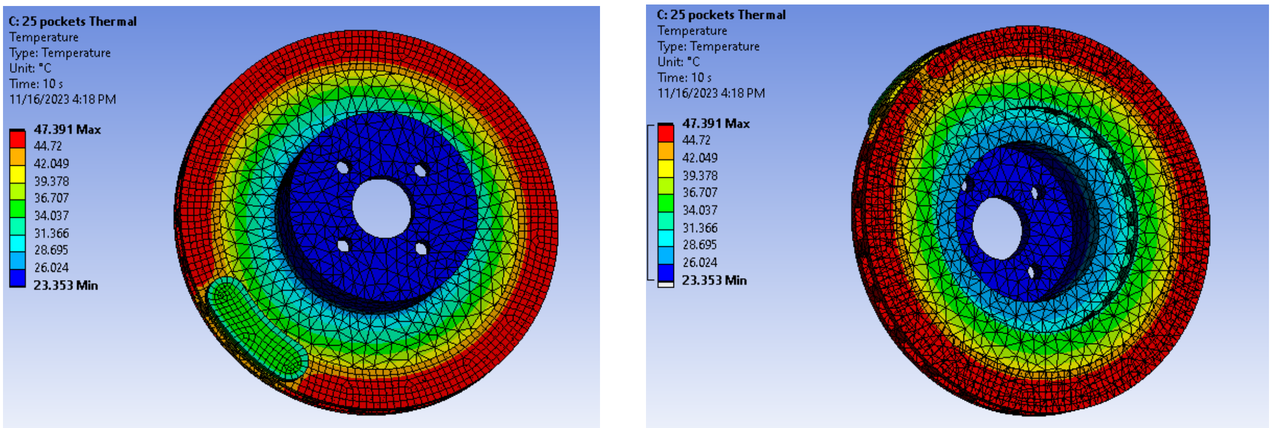

Figure 9 Case 4: Temperature Distribution

4.2.5. Case-5 Design Of Disk Brake With 30 Pockets

In Figure 10, the temperature analysis of the brake disc reveals a peak temperature of 46.805°C in the region near the disk pad contact. Progressing towards the center, the temperature gradually decreases, reaching a minimum of 23.199°C.

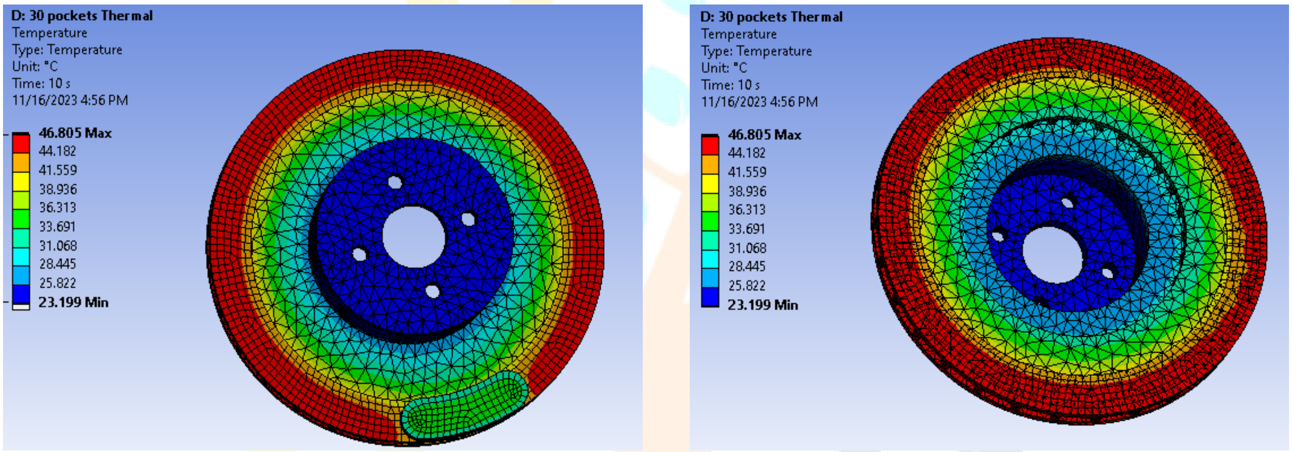

Figure 10 Case 5: Temperature Distribution

This thermal distribution pattern indicates effective heat dissipation, with lower temperatures observed at the central area of the disc. Understanding such temperature variations is crucial for optimizing brake system designs, ensuring efficient heat management, and overall performance in diverse braking conditions.

4.2.6. Case-6 Design Of Disk Brake With 35 Pockets

In Figure 11, the temperature distribution analysis of the brake disc illustrates a peak temperature of 46.305°C near the region of contact with the disk pad. Moving towards the center, the temperature gradually decreases, reaching a minimum of 23.051°C. This thermal profile signifies effective heat dissipation, showcasing lower temperatures at the central portion of the disc. Understanding these temperature variations is crucial for optimizing brake system designs, ensuring efficient heat management, and overall performance across various braking scenarios.

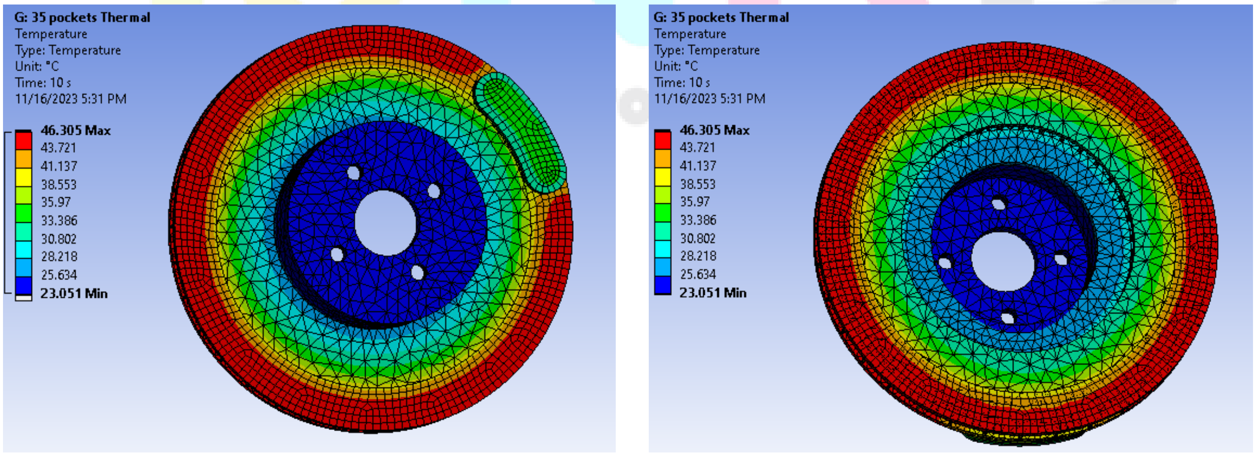

Figure 11 Case 6: Temperature Distribution

The temperature distribution profiles provide valuable insights into the thermal response of the brake disc under examination. Understanding these temperature variations is crucial for optimizing the design of the brake system. Identifying regions of elevated temperatures near the contact area and monitoring the gradual decrease along the length of the disc aids in the development of effective heat dissipation strategies. This detailed thermal analysis contributes to the enhancement of brake disc designs, ensuring optimal performance and reliability under varying braking conditions.

4.3. COMPARISON OF TEMPERATURES

Table 3 Temperature Comparison of all the 7 cases

CASES	Maximum temperature (°C)	Minimum temperature(°C)	Temp. difference
Validation model	52.028	24.716	27.312
Case-1	50.185	23.894	26.291
Case-2	49.042	23.697	25.345
Case-3	48.094	23.519	24.575
Case-4	47.391	23.353	24.038
Case-5	46.805	23.199	23.606
Case-6	46.305	23.051	23.254

When comparing the temperatures listed in Table 3, it is evident that the minimum temperature at the contact surface is recorded in case 6, specifically at 46.305°C. This uniformity in the initial heat flux applied to the disk pad surface across all cases highlights that the dissipation of heat is more efficient in case 6 compared to the other scenarios. The superior design efficiency in case 6 is attributed to the faster rate at which heat is being dissipated. Graphical representations of the maximum and minimum temperatures are illustrated in Figures 12 and 13.

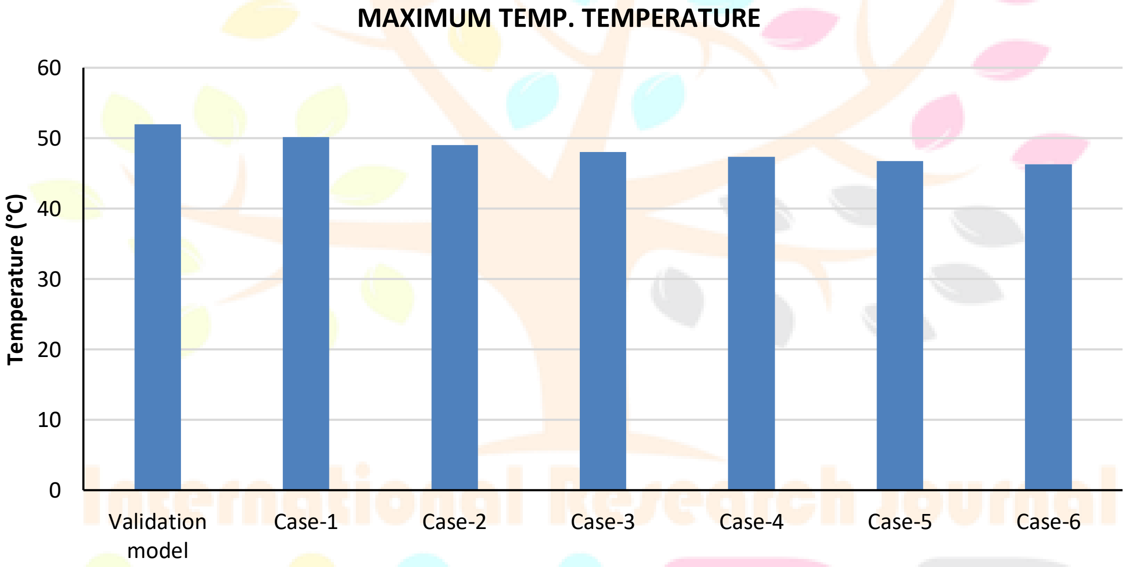

Figure 12 Graphical comparison of max. temperature of the 7 cases

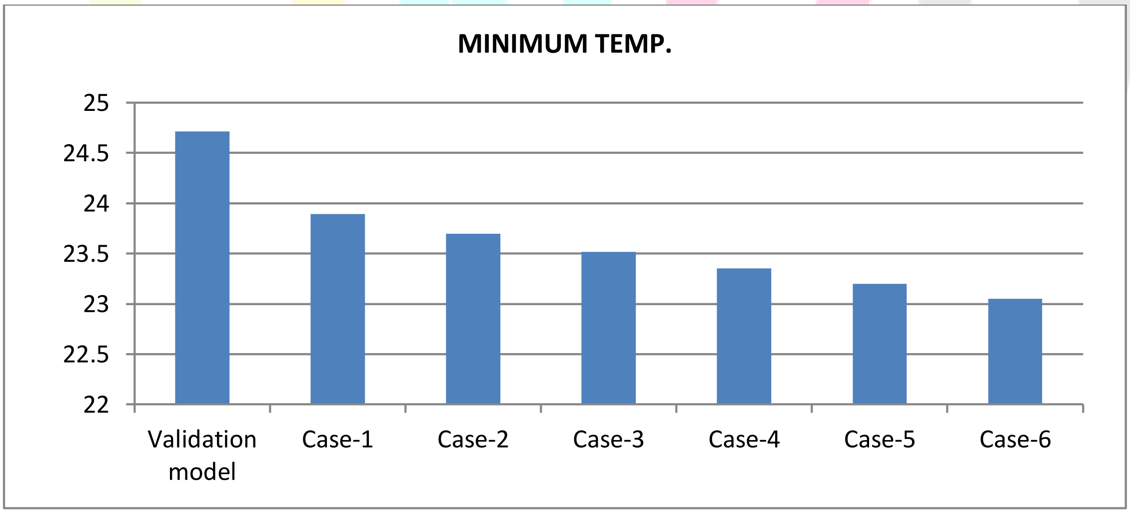

Figure 13 Graphical comparison of min. temperature of the 7 cases

4.4. COMPARISON OF WEIGHT

Table 4 Comparison of weights in all 5 cases

CASES	Weight (Kg)
Validation model	6.075
Case-1	5.29
Case-2	5.08
Case-3	4.86
Case-4	4.65
Case-5	4.43
Case-6	4.22

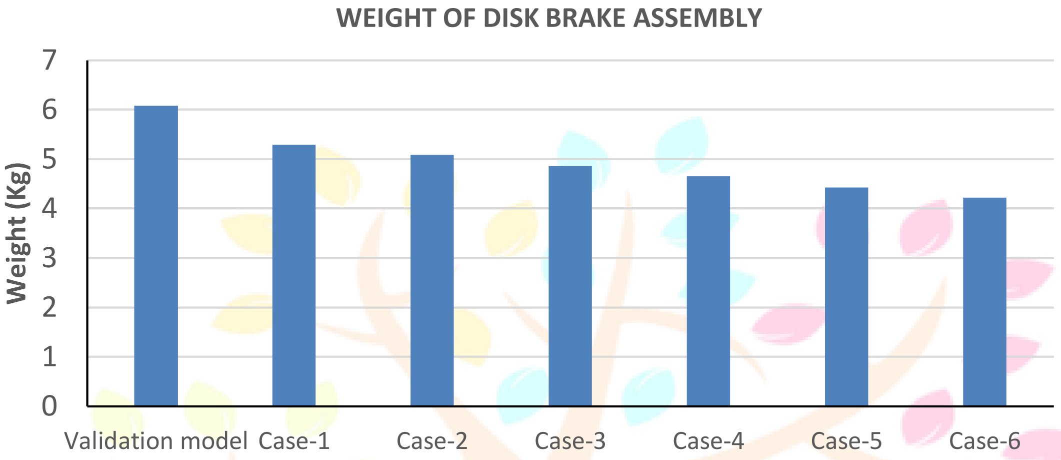

Figure 14 Graphical comparison of the weights in the 5 cases

Case 6 exhibits the lowest weight for the disk brake assembly, recorded at 4.22 kg, as depicted in Figure 14. This weight reduction is attributed to the design's maximum material reduction achieved through an increased number of pockets. The innovative design with enhanced pockets contributes to minimizing overall weight, showcasing the effectiveness of this configuration in optimizing material usage and achieving a lighter disk brake assembly.

5. CONCLUSIONS

Five distinct designs of the disk brake, including the disk pad, were conceptualized to enhance the heat dissipation rate while concurrently minimizing the total weight of the disk assembly. The key findings are summarized below:

- The temperature distribution analysis revealed that the maximum temperature occurs near the disk pad contact region, emphasizing the critical role of this area in heat generation during braking.
- The gradual decrease in temperature from the contact region towards the opposite end of the disc indicates effective heat dissipation mechanisms along the length of the brake disc.
- Among the different design cases, Case 6 demonstrated the highest temperature difference, showcasing superior heat dissipation efficiency.
- Case 6, characterized by a disk brake with both holes on the disk and cuts on the pads, not only exhibited the maximum temperature difference but also offered the minimum weight for the overall disk brake assembly (4.22 kg).
- The weight reduction in Case 6 is attributed to the innovative design with maximum material reduction achieved through an increased number of pockets.

Upon comprehensive analysis of all the results, it is deduced that the design presented in Case 6, featuring a disk brake with maximum pockets, stands out as the most suitable choice for enhancing heat dissipation in the disk brake system.

6. FUTURE SCOPE

To enhance disk brake performance, several key initiatives should be pursued. Firstly, there's a need to optimize design parameters by exploring additional geometric variations, hole patterns, and materials to improve heat dissipation and reduce weight. Secondly, integrating advanced materials with superior thermal conductivity and mechanical properties can further enhance performance. Thirdly, experimental validation in real-world conditions is crucial to verify simulation results. Collaborative research with automotive engineers and manufacturers is essential to align optimized designs with industry standards. Additionally, evaluating environmental impact and exploring smart brake technologies are vital, along with assessing manufacturability and cost implications to ensure practical implementation.

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