UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SIMULATION AND ANALYSIS OF THERMAL AND STRUCTURAL ANALYSIS ON DISK BRAKE USING CAE

MUHAMMAD AMIR BIN AB HALIM

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A thesis submitted
in fulfillment of the requirements for the degree of
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Jurutera Pengajar
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DEDICATION

To my loving parents, whose unwavering support and belief in me have been the pillars of my strength, this thesis is dedicated. Your sacrifices and encouragement have been my inspiration throughout this journey.

To my supervisor Mr. Ahmad Zul Husni Bin Che Mamat whose wisdom and guidance have illuminated my path, this work is a testament to your dedication to nurturing minds.

To my friends, who have been my second family, this thesis stands as a symbol of our shared struggles and triumphs.

And lastly, to all those who dare to dream and strive for knowledge, may this thesis serve as a beacon, inspiring you to reach for the stars.

This is not just my journey, but ours. This thesis is dedicated to you.

ABSTRACT

Brakes serve the purpose of decelerating or halting a moving entity. During the braking process, kinetic energy derived from the velocity of the vehicle is transformed into thermal energy, causing an increase in the disc brake's temperature. To avoid damage to the disc brake or associated components, it is imperative to efficiently dissipate the generated heat into the surrounding atmosphere. One viable approach to enhance this heat dissipation is to augment the surface area exposed to the environment. This strategy is critical in maintaining the integrity and performance of the braking system. This study proposed 4 different profile of disc brake rotors based on dimension of Audi A6 ISO standard with combination ventilation features of groove and vent with different designs which are designed in CATIA. The materials is same for all of the disc brakes which is gray cast iron. The objectives are to model and simulate thermal analysis and structural analysis on the disc brake. Then, identify design modifications that can improve the performance of the disk brake in term of thermal and structure. The study used the transient thermal analysis and transient structural analysis in Ansys Workbench to simulate the performance of disc brake in term of heat distribution, heat dissipation, total deformation and distribution stress. Based on the analysis, the 4 profile disc brake rotors outperformed the base model in thermal performance but not in structural stability. Based on he comparison, Model 3 is the best proposed design in consideration of heat distribution, heat dissipation, total deformation and stress distribution.

ABSTRAK

Brek berfungsi untuk melambatkan atau menghentikan entiti yang bergerak. Semasa proses membrek, tenaga kinetik yang berasal dari kelajuan kenderaan diubah menjadi tenaga haba, menyebabkan peningkatan suhu brek cakera. Untuk mengelakkan kerosakan pada brek cakera atau komponen yang berkaitan, adalah mustahak untuk menghilangkan haba yang dihasilkan ke atmosfera sekitarnya dengan cekap. Satu pendekatan yang boleh dilaksanakan untuk meningkatkan pembuangan haba ini adalah untuk meningkatkan kawasan permukaan yang terdedah kepada alam sekitar. Strategi ini penting dalam mengekalkan integriti dan prestasi sistem brek. Kajian ini mencadangkan 4 profil rotor brek cakera yang berbeza berdasarkan parameter Standard Audi A6 ISO dengan ciri-ciri pengudaraan gabungan alur dan ventilasi dengan reka bentuk yang berbeza yang dibentuk di CATIA. Bahannya sama untuk semua brek cakera yang berwarna besi Tuang kelabu. Objektifnya adalah untuk memodelkan dan mensimulasikan analisis terma dan analisis struktur pada brek cakera. Kemudian, kenal pasti pengubahsuaian reka bentuk yang boleh meningkatkan prestasi brek cakera dari segi terma dan struktur. Kajian ini menggunakan analisis terma sementara dan analisis struktur Sementara di Ansys Workbench untuk mensimulasikan prestasi brek cakera dari segi pengedaran haba, pelesapan haba, ubah bentuk total dan tekanan pengedaran. Berdasarkan analisis, rotor brek cakera profil 4 mengatasi model asas dalam prestasi terma tetapi tidak dalam kestabilan struktur. Berdasarkan perbandingan he, Model 3 adalah reka bentuk terbaik yang dicadangkan dengan mempertimbangkan pengedaran haba, pembuangan haba, ubah bentuk total dan pengedaran tekanan.

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Last but not least, from the bottom of my heart a gratitude to my beloved parents for their endless support, love and prayers. Finally, thank you to all the individual(s) who had provided me the assistance, support and inspiration to embark on my study.

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LIST OF SYMBOLS AND ABBREVIATIONS

ϖ - Heat Partition Coefficient
ξ_d - Thermal Effusivity Of Disc
S_d - Disc Friction Contact Surface
ξ_p - Thermal Effusivity Of Pad
S_p - Pad Friction Contact Surface
ξ - Thermal Effusivity
k - Thermal Conductivity
ρ - Density
C_p - Specific Heat
φ_0 - Arc Angle Pad
d - Diameter
r_1 - Inner Radius In Disc
r_2 - Outer Radius In Disc
r_3 - Inner Radius In Pad
r_4 - Outer Radius In Pad
$\dot{E}$ - Heat Rate Due To Friction
F_f - Friction Force
V - Relative Shear Speed
ω - Wheel Speed
μ - Friction Coefficient
p - Pressure
φ_0 - Arc Angle Pad
$\dot{E}_p$ - Heat Rate Due To Friction On Pad
$\dot{E}_d$ - Heat Rate Due To Friction On Disc
q_1 - Heat Flux On Pad
q_{0_1} - Initial Heat Flux On Pad
q_2 - Heat Flux On Disc
q_{0_2} - Initial Heat Flux On Disc
P_{max} - Maximum Pressure

ω_0 - Wheel Initial Speed
t - Time
t_b - Braking Time
m_v - Mass Of The Vehicle
v_0 - Initial Velocity
D_r - Rim Diameter
D_w - Wheel Diameter
AMC - Aluminium-Metal Matrix Composite
GCI - Grey Cast Iron
CAE - Computer Aided Engineering
CMC - Ceramic Matrix Composite
PAN - Polyacrylonitrile
SiC - Silicon Carbide
Al2O3 - Aluminum Oxide
SS420 - Stainless Steel 420
CC - Carbon Ceramic
AL 6061 - Aluminum 6061 Alloy
AISI 304 - Austenitic Chromium-Nickel Stainless Steel
Cr-V - Chromium Vanadium
FE - Finite Element
FEM - Finite Element Method
TRV - Taper Radial Vane
VDCP - Variable Diameter Ciru

CHAPTER 1

INTRODUCTION

1.1 Background

Disk brakes play an essential role in the braking mechanisms of vehicles and machinery, delivering consistent braking strength and safeguarding the security of occupants and goods (Jule et al., 2021). They work by harnessing the power of friction on a spinning disc to slow down or bring a wheel to a halt (Singh & Scholar, n.d.). When a vehicle comes to a stop, the energy that was propelling it forward is converted into heat energy, resulting in the heating up of brake components, specifically the brake disks. Failure to effectively control and disperse heat can result in brake fade, diminished braking capacity, and potential harm to the brake hardware. Analyzing the thermal characteristics of disk brakes is crucial for enhancing their performance and refining their design.

The simulation and analysis of thermal behaviour on a disk brake using Computer-Aided Engineering (CAE) has become an indispensable tool in the design and development of efficient braking systems. Disk brakes play a crucial role in modern vehicles, providing reliable and controlled deceleration. However, the intense heat generated during braking can lead to thermal degradation, reduced performance, and even failure of the braking system. Therefore, understanding and predicting the thermal behaviour of disk brakes through simulation and analysis using CAE techniques is of paramount importance.

CAE offers a powerful platform for virtual testing and optimization, allowing engineers to assess the thermal performance of a disk brake system under various operating conditions without the need for costly physical prototypes. By utilizing advanced numerical methods and computational models, CAE enables detailed investigations into heat transfer, thermal stresses, and temperature distribution within the disk brake assembly. This information can aid in identifying potential issues, optimizing the design, and enhancing the overall performance and reliability of the brake system.

The refinement of brake system designs is enhanced by the knowledge obtained from simulating and analyzing the thermal behavior of disk brakes with varying designs. As a result, there is an enhancement in the efficiency of braking, as well as an extension in the lifespan of the parts, ultimately leading to heightened safety measures. The utilization of CATIA and ANSYS software empowers engineers to delve into inventive design arrangements, precisely evaluate their heat-connected attributes, and progress the development of disk brake systems that are more effective and dependable.

1.2 Problem Statement

The overall effectiveness and safety of disk brakes are highly dependent on their thermal characteristics. The occurrence of brake fade, lower braking effectiveness, and possible harm to the brake components' structure may arise due to the excessive heat generated while braking. In order to guarantee the effective operation of disk brakes, it is essential to evaluate and study their heat features, particularly when encountering various design arrangements.

The current study on thermal behavior of disk brakes has mostly centered on conducting costly and time-consuming experiments, restricting the exploration of different design options . There are some study on disk brake using simulation method but insufficient factor being considered such as parameter and design of disk brake.

1.3 Research Objective

The main aim of this research is to determine best design for disk brake in thermal performance. The objectives of this research are :

a) To model and simulate the thermal analysis on the disc brake.

b) To model and simulate the structural analysis on the disc brake.

c) To identify design modifications that can improve the performance of the disk brake in term of thermal and structure.

1.4 Scope of Research

The scope of this research are as follows:

- Comparison of various design of disk brake by using same material.
- Use transient thermal analysis and thermal-structural coupled analysis in Ansys.
- Set heat distribution, heat dissipation, thermal stress and structural deformation as parameters for the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Disc brakes are mechanical marvels found in a range of vehicles, from cars and motorcycles to bicycles and airplanes. The brake disc, a circular metal plate, is attached to the wheel hub. When the brakes are engaged, the brake pads squeeze the disc, creating friction and causing the wheel to decelerate (Kajabe & Navthar, n.d.). The brake caliper houses the brake pads and applies pressure to the disc, thanks to pistons or cylinders. Brake pads, made of friction materials, are nestled within the caliper and get pressed against the disc when the brake pedal is activated. Hydraulic disc brakes use brake fluid to transmit force from the pedal to the caliper, activating the pistons and initiating contact between the pads and disc. Mounting hardware secures the caliper and pads to the vehicle's suspension or brake assembly.

When the brake pedal is pressed, the disc brake system converts the wheel's kinetic energy into heat energy through friction. As the hydraulic system applies pressure to the caliper, the brake pads forcefully grip the rotating disc, generating heat. This heat is then dissipated through the disc and other cooling mechanisms. The resulting thermal transfer causes the vehicle to slow down or come to a stop. Disc brakes are celebrated for their impressive stopping power, efficient heat dissipation, and resistance to brake fading, which is the loss of braking performance due to overheating. They offer precise control over braking, allowing for quick response and modulation. Due to their reliability, durability, and consistent performance in various conditions, disc brakes have become the go-to choose in modern vehicles.

The advantages of disc brakes over drum brakes have made them a ubiquitous feature in passenger cars and light trucks. Brake pads and linings, which are friction materials, are specially designed to have a high coefficient of friction. The material chosen depends on the specific braking application, but it must be capable of absorbing and dispersing a substantial amount of heat without compromising braking performance. Analyzing the thermal behavior of brake systems is a critical step in their study since temperature directly influences the thermo-mechanical properties of the structure. Elevated temperatures during braking can lead to issues such as brake fade, premature wear, brake fluid vaporization, bearing failure, thermal cracks, and thermal-induced vibrations. Therefore, accurately predicting the temperature rise in each brake system and assessing its thermal performance during the early design phase is of utmost importance.

CAE, an acronym for Computer-Aided Engineering, revolutionizes the design, analysis, and optimization of various products and systems by utilizing computer software and advanced computational tools. It encompasses a wide range of simulation and analysis techniques that assist engineers in comprehending and predicting the behavior of physical structures, components, and processes. CAE tools enable engineers to create virtual prototypes and simulate the performance of a product or system under different conditions, eliminating the need for physical prototypes. With mathematical models, numerical methods, and algorithms, CAE allows engineers to study and evaluate the behavior of complex systems within a virtual environment.

One of the primary applications of CAE is in structural analysis. Engineers can simulate the structural behavior of components and systems using CAE tools, enabling them to perform stress analysis, deformation analysis, and vibration analysis. These analyzes help determine the strength, integrity, and performance of structures, ensuring they meet design requirements and can withstand operational loads. Additionally, CAE tools facilitate thermal analysis, enabling engineers to simulate and analyze heat transfer and thermal behavior in systems. This includes evaluating temperature distribution, heat dissipation, and thermal management in components and systems such as engines, electronics, and heat exchangers. CAE tools also incorporate optimization algorithms, which help engineers find the most optimal design solutions. They allow for exploring different design options, evaluating performance trade-offs, and optimizing designs based on specific criteria or constraints.

In the automotive industry, extensive research has been conducted to improve vehicle quality and performance, directly impacting product lifespan and customer satisfaction. The automotive brake system plays a crucial role in slowing down or halting a vehicle by converting kinetic energy into thermal energy through friction between the brake pad and the disc. To endure the high temperatures of 400-500°C, brake rotors and brake pad materials must withstand intense mechanical and thermal stresses. Moreover, to prevent surface cracking, judder, and excessive wear on the rubbing surfaces, it is essential to effectively transfer the generated heat (Mahesh & Valavade, 2016). This literature review aims to provide an overview of studies that have utilized CAE tools for simulating and analyzing the thermal behavior of disc brakes. By analyzing various research papers, this review highlights the advantages, methodologies, and outcomes of these studies, emphasizing the pivotal role of CAE in comprehending and optimizing the thermal performance of disc brakes.

2.2 Material and Tribology of Disc Brake

Disc brakes are critical components in various modes of transportation, providing reliable and efficient stopping power. The evolution of disc brake technology has been greatly influenced by advancements in material science and tribology. Material science focuses on developing brake pad and disc rotor materials with improved characteristics such as wear resistance, thermal conductivity, and friction coefficient. Tribology, on the other hand, delves into the study of friction, lubrication, and wear, aiming to optimize the performance and durability of disc brakes. This essay explores the significant benefits of material science and tribology research in disc brakes, highlighting how these studies have revolutionized braking systems, enhanced safety, and improved the overall driving experience.

Material science and tribology research have played a pivotal role in enhancing the performance and safety of disc brakes. By studying the properties and behavior of brake pad and disc rotor materials, researchers have been able to develop advanced materials with superior wear resistance. This translates to longer-lasting brakes that maintain their effectiveness over extended periods, reducing the need for frequent replacement and enhancing overall safety on the road. Moreover, the research conducted in tribology has led to the development of materials with optimized friction characteristics. The friction coefficient is a crucial factor in determining the braking efficiency and effectiveness of disc brakes.

Through tribological investigations, researchers have been able to identify and develop materials that provide consistent and reliable friction performance across various operating conditions, ensuring predictable and controlled stopping power. Additionally, the field of tribology has contributed to understanding the lubrication requirements of disc brakes. Lubrication plays a vital role in reducing friction, minimizing wear, and dissipating heat generated during braking. Through tribological research, scientists have identified suitable lubricants and developed lubrication strategies that improve the overall performance and longevity of disc brakes. This, in turn, reduces the likelihood of brake failure, enhances safety, and instils confidence in the braking system for both drivers and passengers. Material science and tribology research have significantly impacted the durability and maintenance requirements of disc brakes.

By investigating the wear mechanisms of brake pad and disc rotor materials, researchers have been able to identify ways to mitigate wear and develop materials that exhibit improved resistance to degradation. This translates to longer-lasting brakes that require less frequent replacement, reducing maintenance costs and vehicle downtime. Furthermore, tribological research has contributed to the understanding of the complex interactions between brake pads and disc rotors. These interactions can generate heat and result in excessive wear, compromising the durability of the braking system. Through tribological studies, researchers have developed innovative designs, such as slotting and cross-drilling, which enhance heat dissipation and reduce wear, leading to increased longevity of disc brakes.

In addition, material science research has explored the use of advanced materials, such as carbon-ceramic composites, which exhibit superior wear resistance, high thermal conductivity, and reduced weight compared to traditional brake materials. These materials not only enhance the durability of disc brakes but also contribute to the overall weight reduction of the vehicle, improving fuel efficiency and reducing environmental impact.

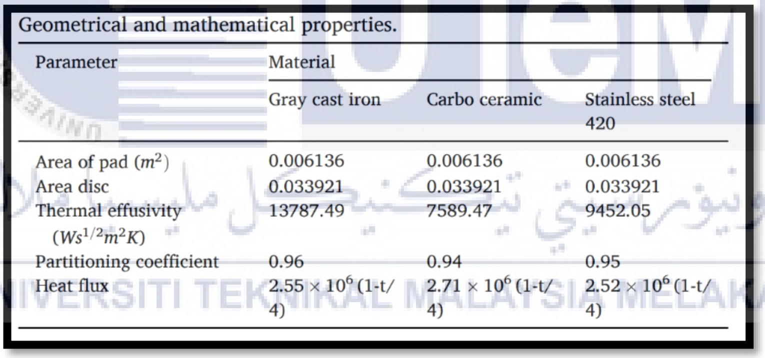
Material science and tribology research have enabled the optimization of disc brake performance under various operating conditions. Disc brakes experience a wide range of environments, including different temperatures, speeds, and surface conditions. Understanding how brake pad and disc rotor materials behave under these conditions is crucial to ensuring consistent and reliable braking performance. Through material science research, scientists have identified the thermal properties of brake pad and disc rotor materials, such as their thermal conductivity and heat capacity. This knowledge allows for the development of materials that can effectively dissipate heat.

For the sake of development of disc brake performance, various material being studied in order to achieve high performance disc brake. (Hefei gong ye da xue et al., n.d.) a study of comparison between gray cast iron, carbon ceramic and stainless steel 420 has been done.

Gray cast iron (GCI) is a popular automotive brake disc material by virtue of its high melting point as well as excellent heat storage and damping capability. GCI is also attractive because of its good castability and machinability, combined with its cost-effectiveness. Generally, gray cast iron is made of iron (Fe) with a high carbon content and the presence of graphite flakes. The carbon content in gray cast iron is typically between 2.5% and 4%, which is higher than that of other types of cast iron. The graphite flakes give the material its characteristic gray color and contribute to its unique properties.

Carbon ceramic also known as ceramic matrix composite (CMC), is a type of material that combines carbon fibers with a ceramic matrix. It is a highly engineered composite material that exhibits exceptional properties such as high strength, high temperature resistance, low thermal expansion, and excellent thermal conductivity. Carbon ceramic is typically composed of carbon fibers, such as carbon nanotubes or carbon fibers derived from materials like polyacrylonitrile (PAN) or pitch, embedded within a ceramic matrix. The ceramic matrix can be made from various ceramic materials such as silicon carbide (SiC), aluminum oxide (Al2O3), or a combination of different ceramics. Carbon ceramic offers substantial benefits in terms of performance - in both wet and dry conditions - weight, comfort, corrosion resistance, durability, and high-tech appeal.

Stainless steel 420 is a martensitic stainless-steel belonging to the 400 series. It is characterized by its high strength, moderate wear resistance, and good corrosion resistance. Comprised mainly of chromium, stainless steel 420 also contains carbon, manganese, and silicon. With a carbon content ranging from 0.15% to 0.40%, it can be hardened through heat treatment processes like quenching and tempering. This property makes it suitable for applications that require high strength and wear resistance, such as surgical instruments, cutting tools, and mechanical components. However, it is important to note that stainless steel 420 offers lower corrosion resistance compared to austenitic stainless steels. While it performs well in mild environments, its resistance to corrosion may vary depending on the specific conditions and corrosive agents present. The geometrical and mathematical properties of the materials stated in Table 2.2.1(Tauviqirrahman et al., 2023).



Geometrical and mathematical properties.

Parameter	Material		
	Gray cast iron	Carbo ceramic	Stainless steel 420
Area of pad (m^2)	0.006136	0.006136	0.006136
Area disc	0.033921	0.033921	0.033921
Thermal effusivity $(Ws^{1/2}m^2K)$	13787.49	7589.47	9452.05
Partitioning coefficient	0.96	0.94	0.95
Heat flux	2.55×10^6 (1-t/4)	2.71×10^6 (1-t/4)	2.52×10^6 (1-t/4)

Table 2.2.1 : Geometrical and Mathematical Properties of Materials

From the study, gray cast iron shows highest value in maximum temperature over time than stainless steel 420 and gray carbon ceramic (Figure 2.2.1).

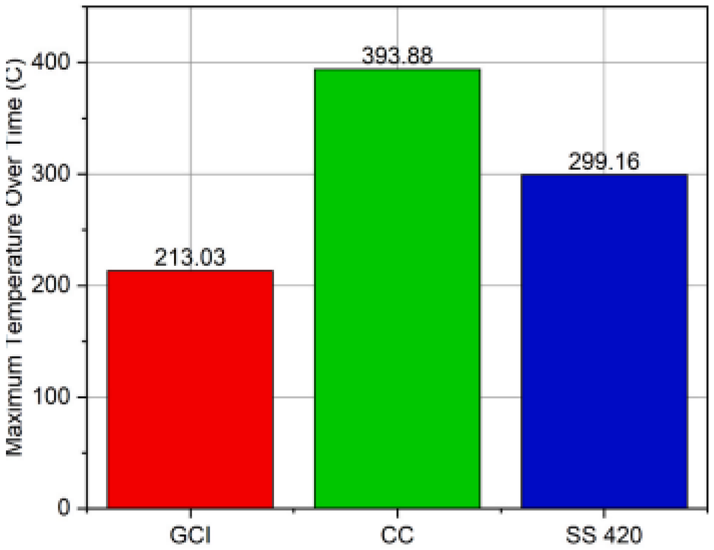
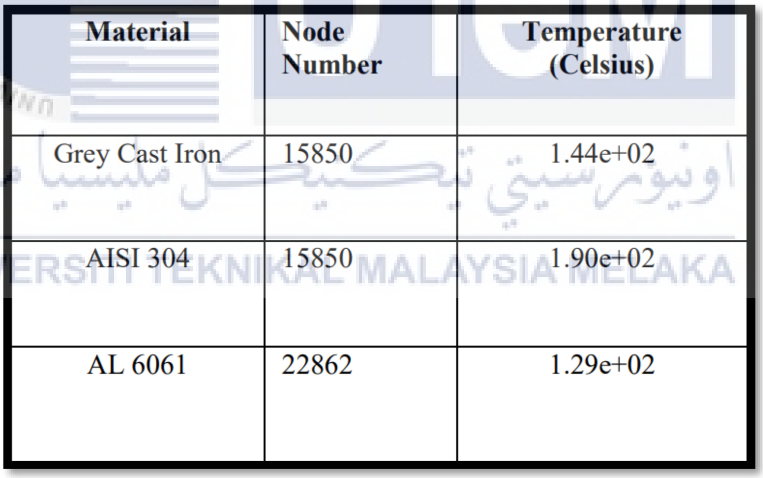


Figure 2.2.1 : Max Temperature over Time between Gray Cast Iron, Carbon Ceramic and Stainless Steel 420

Thermal conductivity can be the factor of influencing rise of disc brake's temperature. The thermal conductivity of the brake disc material determines how effectively it can transfer heat away from the braking surface. Materials with higher thermal conductivity can dissipate heat more efficiently, reducing the temperature rate on the disc. Gray cast iron has a moderate thermal conductivity, which allows it to efficiently transfer heat away from the braking surface. This helps in distributing the generated heat across a larger area of the disc, reducing the temperature rate. Specific heat capacity of the material refers to its ability to absorb and store heat. Materials with higher specific heat capacity can absorb more heat energy before reaching higher temperatures, resulting in a lower temperature rate on the disc. Gray cast iron has a relatively high specific heat capacity compared to some other brake disc materials. This means it can absorb a significant amount of heat energy before its temperature increases significantly. This helps in slowing down the temperature rate rise during braking. Thermal stability of the material refers to its ability to withstand high temperatures without undergoing significant changes in its structure or properties. Materials with good thermal stability can handle higher temperature rates without degrading or compromising performance. Gray cast iron has good thermal stability, meaning it can withstand high temperatures without significant degradation or changes in its structure. This stability helps in maintaining the performance and integrity of the disc under prolonged or repeated braking, minimizing the temperature rate. Wear resistance of the brake disc material is important because excessive wear can affect the disc's ability to dissipate heat. If the material wears unevenly or develops grooves, it can impair heat transfer and lead to higher temperatures. Gray cast iron is known for its wear resistance, which is essential for maintaining the disc's surface integrity and preventing excessive frictional heating. A smooth and wear-resistant surface reduces the temperature rate by minimizing localized hot spots and uneven heat distribution.

Meanwhile in (Tauviqirrahman et al., 2023), gray cast iron not be the lead in performance in comparison between gray cast iron (GCI), aluminum 6061 alloy (AL 6061) and AISI 304 stainless steel (AISI 304). Aluminium alloy lead the performance in term on temperature on brake disc. The result can be referred in Table 2.2.2.



Material	Node Number	Temperature (Celsius)
Grey Cast Iron	15850	1.44e+02
AISI 304	15850	1.90e+02
AL 6061	22862	1.29e+02

Table 2.2.2 : Simulation Result based on Material

This alloy is made up of 97.9% of Aluminium, Si-0.6 %, Magnesium 1.0%, Cuprum 0.28%, and Chromium- 0.2% (Mugilan et al., 2022). Chromium (Cr), 0.7 to 0.9% Manganese(Mn), Carbon(C) of 0.48 to 0.53%, Silicon(Si) of 0.15 to 0.35%, Vanadium(V) of 0.15 to 0.3%, Sulphur(S) of 0 to 0.04% and finally 0 to 0.035% of Phosphorous(P).

The analysis conducted by (Phaneendra et al., 2018) using Al 6262 T-9 allows using the materials of this class. The addition of different alloying elements can modify characteristics such as strength, hardness, corrosion resistance, and thermal conductivity. Aluminum alloys are widely used in various industries, including automotive, aerospace, construction, and manufacturing, due to their lightweight nature, excellent corrosion resistance, and good mechanical properties. Aluminum alloys with higher thermal conductivity can enhance heat transfer and dissipate heat more effectively. Alloy compositions with elements like copper or magnesium can improve the thermal conductivity of aluminum alloys.

Comparison between Gray Cast Iron, Titanium Ti-6Al-4V (Grade 5) and Chromium Vanadium Steel has been conducted in (Abhishikt et al., 2020a) . It’s been tested in 2 different design of disk brake which are drilled and ventilated disc and result shown in Table 2.2.3.

<table>
<tr><th colspan="5">TABLE 2.2.4</th></tr>
<tr><th colspan="5">Result summary of Grey Cast Iron Discs.</th></tr>
<tr><th></th><th>Max deformation (mm)</th><th>Von-Mises Stress (MPa)</th><th>Temperature (°C)</th><th>Heat Flux (W/mm^2)</th></tr>
<tr><td rowspan="2">Ventilated disc rotor</td><td rowspan="2">0.000059853</td><td>0.32351 (max)</td><td>253.09 (max)</td><td>0.42955 (max)</td></tr>
<tr><td>0.00051638(min)</td><td>62.154 (min)</td><td>0.0038181 (min)</td></tr>
<tr><td rowspan="2">Drilled contour disc rotor</td><td rowspan="2">0.000030254</td><td>0.15258 (max)</td><td>320.01 (max)</td><td>0.70072 (max)</td></tr>
<tr><td>0.0000621 (min)</td><td>75.598 (min)</td><td>0.0023646 (min)</td></tr>
<tr><th colspan="5">Result summary of Titanium Ti-6Al-4 V (Grade 5) Discs.</th></tr>
<tr><th></th><th>Max deformation (mm)</th><th>Von-Mises Stress (MPa)</th><th>Temperature (°C)</th><th>Heat Flux (W/mm^2)</th></tr>
</table>

Ventilated disc rotor	0.000053999	0.31734 (max)	396.55 (max)	0.26093 (max)
		0.0002319 (min)	22.655 (min)	0.0000707 (min)
Drilled contour disc rotor	0.000023083	0.11057 (max)	815.09 (max)	0.55553 (max)
		0.0000263 (min)	23.723 (min)	0.0001058 (min)
Result summary of Chromium-Vanadium Steel of Discs.				
	Max deformation (mm)	**Von-Mises Stress (MPa)**	**Temperature (°C)**	**Heat Flux (W/mm^2)**
Ventilated disc rotor	0.000035801	0.3227 (max)	216.22 (max)	0.34659 (max)
		0.0005112 (min)	50.897 (min)	0.0027619 (min)
Drilled contour disc rotor	0.000018683	0.16141 (max)	329 (max)	0.67858 (max)
		0.0000690 (min)	69.308 (min)	0.0020751 (min)

Table 2.2.3 : Result of Structural Analysis

For drilled disk, however, out of these three materials, Chromium-Vanadium steel constructed a smaller maximum temperature in the ventilated disc, about 216.22 C and its leading the Titanium Ti-6Al-4V (Grade 5) which is the alloy composition consists of Aluminium of 6%, Iron of maximum 0.25%, Oxygen of maximum 0.2%, Titanium of 90%, and Vanadium of 4% .

The following most efficient maximum temperature is attained in the grey cast iron ventilated disc of about 253.09 C. Chromium-Vanadium steel, commonly known as Cr-V steel, is a type of alloy steel that contains chromium and vanadium as primary alloying elements. While the specific properties of Cr-V steel can vary depending on the exact composition, it is known for its excellent strength, hardness, and durability. Cr-V steel generally has higher thermal conductivity compared to other materials like cast iron or some aluminum alloys. This allows it to efficiently transfer heat away from the braking surface and distribute it over a larger area, aiding in heat dissipation and reducing maximum temperature. The alloying elements, particularly chromium, in Cr-V steel contribute to its ability to withstand high temperatures without significant degradation. This improves the heat tolerance of the steel, allowing it to sustain lower maximum temperatures without experiencing excessive wear or deformation. Cr-V steel has a thermal expansion coefficient that matches well with other brake system components, such as brake pads and calipers. This minimizes the risk of uneven expansion or binding between the various parts, reducing the likelihood of temperature spikes in the disc. The composition and hardness of Cr-V steel allow for effective friction management during braking. It can handle the heat generated by friction between the brake pads and the disc, reducing the temperature rise and maintaining lower maximum temperatures.

The drilled contour disc with grey cast iron as the material produced best temperature gradient among the other materials with a maximum temperature of 320.01 C, followed by the Chromium-Vanadium steel drilled contour disc with 329 C as the maximum temperature. Gray cast iron has a relatively high thermal conductivity compared to some other brake disc materials. This property allows for efficient heat transfer from the braking surface to the surrounding air, promoting heat dissipation and helping to maintain a more uniform temperature gradient. Gray cast iron has a relatively high specific heat capacity, meaning it can absorb and store a significant amount of heat energy. This property helps to slow down the temperature rise in the disc, resulting in a more gradual temperature gradient and preventing localized overheating. Gray cast iron has good thermal stability, allowing it to withstand high temperatures without significant deformation or structural changes. This property helps maintain the integrity of the disc and ensures that the temperature gradient remains consistent even under demanding braking conditions. Although perform in term of temperature degree, based on its result of deformation, gray cast iron is not superior in crack resistance and make it only suitable for solid disc.

2.3 Isotropic and temperature-independent material characteristics

Based on (Dubale et al., 2021), the amount of heat produced by friction is directly proportional to the frictional force. A part of this heat is taken up by the disc, while the rest is absorbed by the bearing. It’s assumed that all energy from friction is transformed into heat energy, and the parameters define the heat partition coefficient. Both the brakes and bearings can receive the heat energy produced at the brake friction interface. As per (Dubale et al., 2021), the heat partition coefficient can also be interpreted as a form of relative braking energy. The partition coefficient is defined for this particular analysis as :

$$\varpi = \frac{\xi_d S_d}{\xi_d S_d + \xi_p S_p} \quad \textbf{(1)}$$

The heat produced by friction is distributed across the contact surfaces in a shear contact with a high Peclet number. This distribution is significantly affected by the geometry, thermo-physical properties of the contact material, and the conditions of contact. The thermal effusivity of the disc and pad are denoted by ξ_d and ξ_p, respectively. Factors such as material density, heat capacity, and thermal conductivity all have an impact on thermal effusivity. The concept of thermal effusivity is defined as follows:

$$\xi = \sqrt{\mathrm{k}\rho C_p} \qquad \textbf{(2)}$$

Thermal effusion provides a measure of a material's ability to store and transfer thermal energy with its environment. It is computed as the square root of the product of thermal conductivity, density, and specific heat. In this context, Sp and Sd represent the friction contact surfaces of the pad and disc, respectively. They are calculated as follows:

$$\mathrm{S}_p = \varphi_0 \int_{r_1}^{r_2} r dr \qquad \textbf{(3)}$$

$$\mathrm{S}_d = 2\pi \int_{r_1}^{r_2} r dr \qquad \textbf{(4)}$$

The heat generated between the pad and the disc's contact area during braking is due to the microplastic deformation caused by the frictional force. This heating is essentially the conversion of mechanical energy into heat energy. To determine the heat flow in a brake system component, the rate of heat energy is divided by the component's surface contact area. The surfaces of the disc and pad come into contact with each other. A specific formula is used to calculate the amount of heat produced by friction between different surfaces :

$$\mathrm{d\dot{E}} = \mathrm{dp} = \mathrm{V}\mathrm{d}F_f = \mathrm{r\omega\mu p}\varphi_0\mathrm{rdr} \qquad \textbf{(5a)}$$

$$\mathrm{d\dot{E}} = \mathrm{d}\dot{E}_p + \mathrm{d}\dot{E}_d \qquad \textbf{(5b)}$$

$$\mathrm{d}\dot{E}_p = (1 - \varpi)\mathrm{dp} = (1 - \varpi)\mathrm{\omega\mu p}\varphi_0 r^2\mathrm{dr} \qquad \textbf{(5c)}$$

$$\mathrm{d}\dot{E}_d = \varpi\mathrm{dp} = \varpi\mathrm{\omega\mu p}\varphi_0 r^2\mathrm{dr} \qquad \textbf{(5d)}$$

V represents the relative shear velocity, while $\mathrm{d}F_f$ stands for the frictional force, which is dependent on the friction coefficient. The symbol $\mathrm{d\dot{E}}$ denotes the rate of heat production due to friction between two components in shear contact. The friction coefficient is computed by multiplying the applied normal load by the measured tangential force. The symbols $\mathrm{d}\dot{E}_p$ and $\mathrm{d}\dot{E}_d$ represent the amount of heat absorbed by the pad and disc, respectively.

Rate of heat energy by each component's surface contact area respectively are :

a. Heat Flux for Pad

$$q_1(r,t) = \frac{\mathrm{d}\dot{E}_p}{\mathrm{d}\dot{S}_p} = (1 - \varpi)\mu p(t) r \omega(t) \quad \textbf{(6a)}$$

$$q_{0_1}(r) = q_1(r,0) = (1 - \varpi)\mu p r \omega_0 \quad \textbf{(6b)}$$

Combine $p = P_{max}\frac{r_4}{r}$ into Equation **(6a)** resulting,

$$q_1(r,t) = \frac{\mathrm{d}\dot{E}_p}{\mathrm{d}\dot{S}_p} = (1 - \varpi)\mu P_{max} r_4 \omega_0 (1 - \frac{t}{t_b}) \quad \textbf{(6c)}$$

b. Heat Flux for Disc

$$q_2(r,t) = \frac{\mathrm{d}\dot{E}_d}{\mathrm{d}\dot{S}_d} = \frac{\varphi_0}{2\pi}\mu\varpi p(t) r \omega(t) \quad \textbf{(7a)}$$

$$q_{0_2}(r) = q_2(r,0) = \frac{\emptyset_0}{2\pi}\mu\varpi p r \omega_0 \quad \textbf{(7b)}$$

Combine $p = P_{max}\frac{r_4}{r}$ into Equation (7a) resulting,

$$q_2(r,t) = q_{0_2}(r) * (1 - \frac{t}{t_b}) = \frac{\emptyset_0}{2\pi}\mu\varpi P_{max} r_4 \omega_0 (1 - \frac{t}{t_b}) \quad \textbf{(7c)}$$

2.4 Geometry Optimiztion in Performance of Disc Brake

Geometry optimization of a disc brake involves the systematic process of improving the design and configuration of various brake components to enhance braking performance. The significance of geometry optimization in enhancing disc brake performance cannot be overstated. Geometry optimization is one of the key for braking performance.

By carefully designing and optimizing the geometry of brake components, engineers can achieve superior braking performance, reduce brake fade, improve cooling efficiency, and enhance the overall reliability of the braking system. Effective heat dissipation is essential for maintaining consistent braking performance and preventing brake fade. Geometry optimization plays a vital role in enhancing heat dissipation and cooling efficiency in disc brakes. Optimizing the shape and dimensions of the brake rotor can significantly improve heat dissipation(Roy & Bharatish, 2020).

Engineers can explore various designs, including cross-drilled, slotted, or combination rotors, to enhance airflow and facilitate the quick evacuation of hot gases generated during braking. These designs create more surface area for heat transfer, reducing the risk of brake fade and ensuring consistent braking performance(Korba et al., 2021). Additionally, the design of the ventilation system, such as the shape and size of cooling vanes or channels, influences the cooling efficiency. Properly designed ventilation can enhance air circulation within the brake assembly, dissipating heat more effectively. By optimizing the ventilation geometry, engineers can prevent excessive brake temperatures and minimize the risk of thermal damage(Korba et al., 2021).

Geometry optimization also plays a crucial role in improving the frictional performance and contact between the brake pads and rotor. Optimizing the contact area between the brake pad and rotor enhances braking efficiency. Engineers can carefully design the shape and dimensions of the pad surface to maximize contact and ensure uniform pressure distribution during braking. By optimizing the contact geometry, engineers can minimize pad wear, reduce noise and vibration, and improve overall braking feel and performance.(Yoon et al., 2022) stated that the irregular temperature zone that allows thermoelastic brake discs and pads to adjust the surface status and surface pressure among brake discs and pads, which are significantly affected on the essential brake properties such as vibration, noise and friction. Furthermore, optimizing the shape of the brake rotor's surface can enhance the pad-to-rotor interface. Surface texturing techniques, such as grooving or slotting, can improve the initial "bite" and ensure consistent frictional performance throughout the braking cycle. These optimized rotor surfaces help to maintain effective frictional contact, reducing brake fade and improving the overall braking performance(Borawski et al., 2020).

Geometry optimization also focuses on reducing the weight of brake components, particularly the brake rotor. Reducing the unsprung mass has numerous benefits for vehicle performance. By optimizing the rotor geometry, engineers can reduce the overall weight of the brake system without compromising structural integrity. A lighter brake rotor reduces the unsprung mass, improving vehicle handling, suspension response, and overall agility. Moreover, reduced unsprung mass enhances tire grip, contributing to improved traction and braking performance. Weight reduction through geometry optimization also has implications for fuel efficiency and environmental sustainability. Lighter brake components contribute to overall vehicle weight reduction, leading to improved fuel economy and reduced emissions.

Geometry optimization strategies require validation through performance testing. Physical testing allows engineers to evaluate the effects of optimized geometries on the actual braking performance. Performance testing involves assessing braking efficiency, fade resistance, heat dissipation, and overall durability. By comparing the performance of optimized geometries with traditional designs, engineers can validate the effectiveness of geometry optimization in enhancing disc brake performance. Real-world testing provides valuable data to fine-tune the design and make necessary adjustments. By carefully designing and optimizing the geometry of brake components, engineers can achieve enhanced heat dissipation, cooling efficiency, and frictional performance.

Although being implemented in motorcycle, study of various forms of vented holes in a disc brake in (Tauviqirrahman et al., 2023) can be considered because its still significance as many research are related to vented holes feature such as in (Jaiswal et al., n.d.), (Belhocine & Zaidi Wan-Omar, n.d.) and (Hefei gong ye da xue et al., n.d.) who tested different kinds of disc brakes and found that brakes with radial vanes caused the most resistance, while solid disc brakes caused the least. However, solid disc brakes can't cool down as well as brakes with vents or vanes. Researchers found out that the disc with grooves was the best. It can be conclude that the more holes in the brake disc, the better it cools down. But there is no discussion about how holes affect the bends or twists of disc. (Choudhary et al., 2022) explore the improvement of braking performance by varying the angle of rotation of ventilation holes on disc brake.

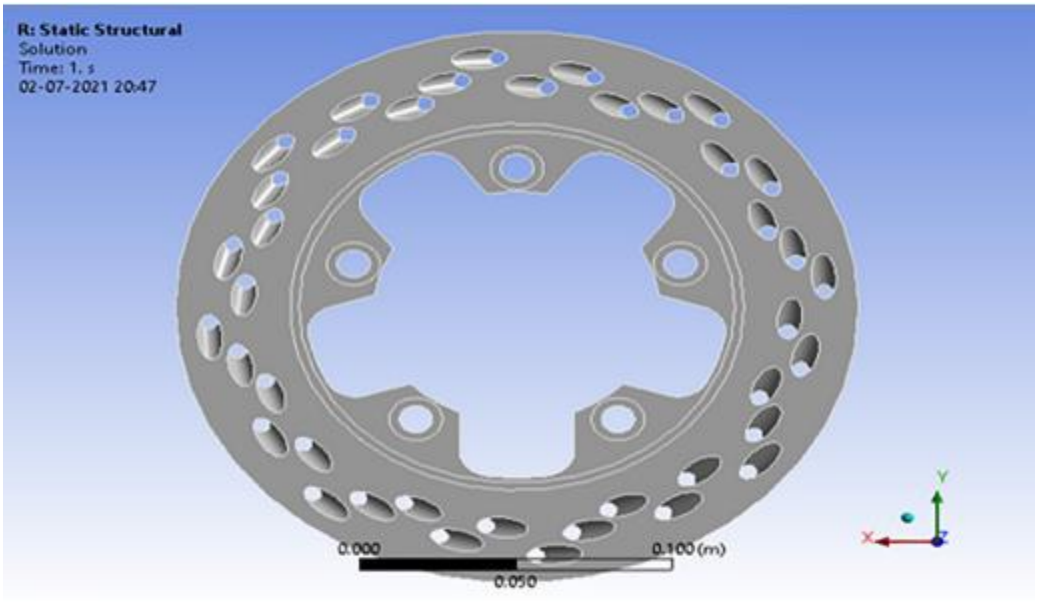


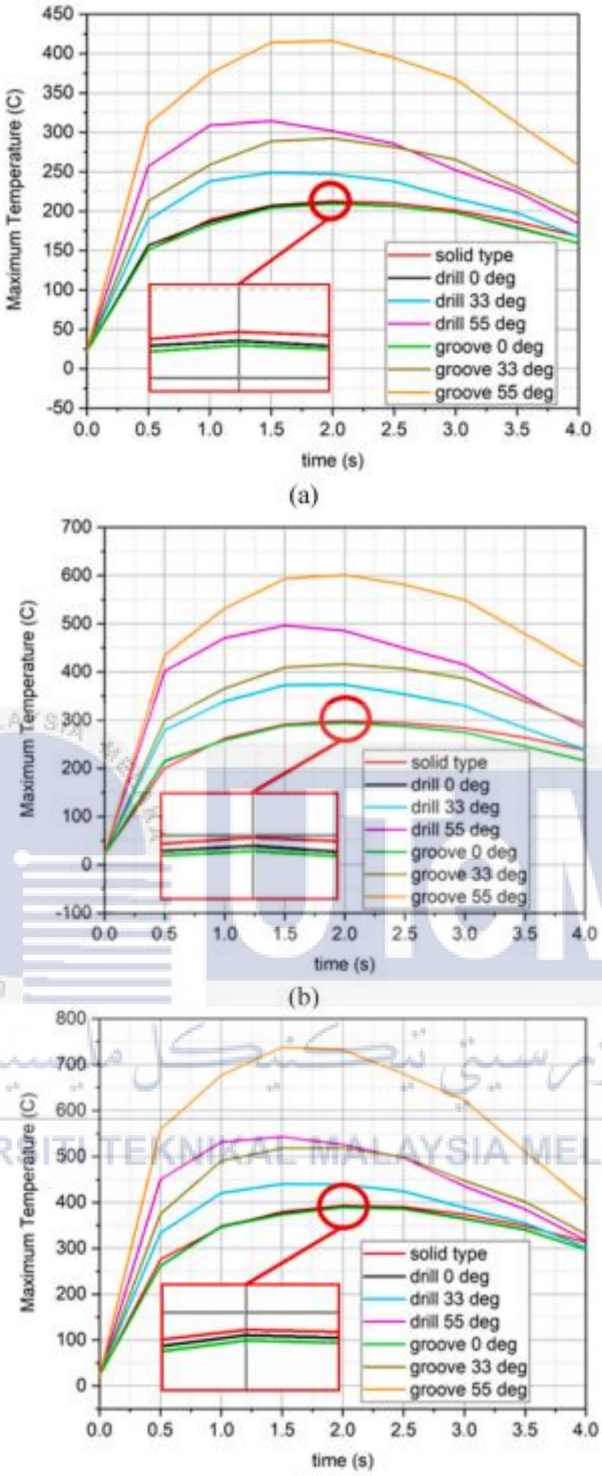
Figure 2.3.1 : Design of Alternate Disc 7

Angle of Rotation (Degrees)	Total Deformation (m)	Equivalent Stress (Pa)	Temperature (°C)	Maximum Heat Flux (W/m^2)
0	7.52E-05	5.03E + 08	232.3	3.61E + 06
1	7.31E-05	4.70E + 08	226.8	3.80E + 06
2	6.85E-05	3.91E + 08	217.93	3.45E + 06
3	6.10E-05	3.88E + 08	203.87	3.44E + 06
4	5.50E-05	4.06E + 08	187.95	3.29E + 06
5	5.01E-05	4.25E + 08	181.56	3.97E + 06
6	4.48E-05	3.98E + 08	166.15	4.67E + 06
7	3.94E-05	4.35E + 08	160.39	2.82E + 06

Table 2.3.1 : Result of Thermal and Structural Analysis in Varying Angle of Ventilation Hole

Table 2.3.1 show that alternate disc 7 with 7 degree angle of rotation is the best choice for a disc brake rotor because it doesn't get too hot and doesn't bend too much. The new disc 7 is better than the regular disc brake. When compared base disc which is with 0 degree angle of rotation. Alternate disc 7 temperature is 160.39 ℃ while the base disc is 232.3 ℃. It can reduce the heat by about 30%.In term of total deformation, alternate disc 7 is 3.94e-05 m while base disc is 7.52e-05 m. The bending improved by about 47%. While equivalent stress for alternate disc 7 is 4.35e-08 Pa and base disc is 5.03e-08 Pa. The pressure achieved improvement by about 13%. If we make the disc colder and don't bend it as much, it will last longer. Therefore, we can say that the seventh alternate disc lasts longer than any other design.

In (Hefei gong ye da xue et al., n.d.), to help brakes cool down better, we suggest changing the angles of the holes in the brake disc. Based on the result (Figure 2.3.2), adding the angles of the holes in the brake makes it able to withstand hotter temperatures. In some areas, the heat gets strong because of the shape getting smaller.



(a)

(b)

(c)

Figure 2.3.2 : Comparison of Thermal Performance between GCI, Stainless Steel & Carbon Ceraimic

In (Sathishkumar et al., 2020), a certain type of brake discs were studied to improve the way they release heat and get an even temperature distribution. They were designed with circular pillars of different sizes (Figure 2.3.3).

(a) Section of TRV rotor (b) Section of VDCP1 rotor

(c) Section of VRCP2 rotor (d) Section of VRCP3 rotor

Figure 3. Different flow passages of rotor geometry configurations.

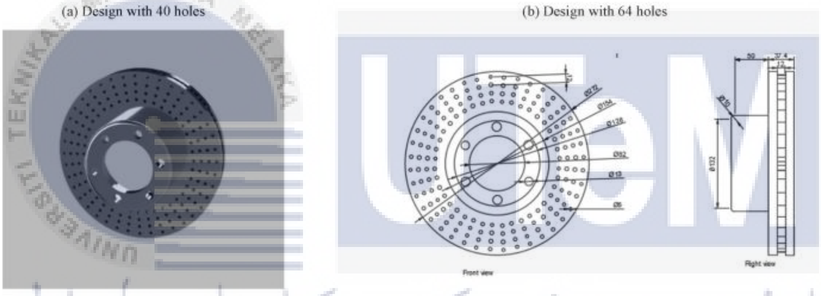
Figure 2.3.3 : Circular Pattern of Vent

CFD code used in this work was validated with experimental results obtained by conducting experiments on a test rig. From the test, it can be concluded that the Variable Diameter Circular Pillar 1 (VDCP1) rotor configuration holds significant promise for modern high-speed vehicles, as it offers enhanced heat transfer capabilities when compared with Taper Radial Vane (Tr. By optimizing the heat transfer coefficient and heat flux, this rotor configuration can effectively dissipate heat and maintain more favourable temperature conditions during braking. The results highlight the potential for improved performance and reliability of brake systems in high-speed applications when utilizing the VDCP1 rotor configuration.

In (Mugilan et al., 2022), three different designs with 40 degree, 64 degree and 160 degree drilled holes will be made in the brake rotor and a comparative study has been made between these designs to select the best design (Figure 2.3.4).

(a) Design with 40 holes

(b) Design with 64 holes



(c) Design with 160 holes

(d) 2D drawing of the design

Fig. 2. CAD models of the brake rotor.

Figure 2.3.4 : Variant of Degree Drilled Holes

Thermal analysis is performed with the fusion 360 software with three different materials of the best design obtained from the previous study and simulation performed to determine the heat flux and temperature distribution (Figure 2.3.5). The pattern with 160 holes cools down better than ones with 40 and 64 holes. It also handles heat better and reduces the coldest temperature of the disc to 41.38 C.

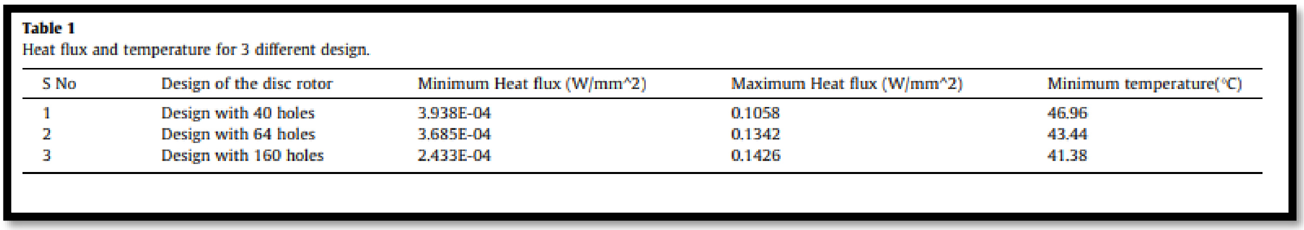


Table 1
Heat flux and temperature for 3 different design.

S No	Design of the disc rotor	Minimum Heat flux (W/mm^2)	Maximum Heat flux (W/mm^2)	Minimum temperature(°C)
1	Design with 40 holes	3.938E-04	0.1058	46.96
2	Design with 64 holes	3.685E-04	0.1342	43.44
3	Design with 160 holes	2.433E-04	0.1426	41.38

Table 2.3.2 : Heat Flux and Temperature for 3 Different Designs

The study by (Belhocine & Zaidi Wan-Omar, n.d.) provides a comprehensive investigation into the thermo-mechanical behavior of three different disc brake profiles. They developed a computer model to simulate the thermal and structural changes in brake discs under intense braking conditions. The finite element method was employed to quantify the heat and stress levels in the disc brakes. In a similar vein, (Abhishikt et al., 2020) designed a disc brake with radial grooves and used ANSYS software for transient structural and thermal analysis. Their study focused on the temperature changes in the discs due to generated heat flux. (Ahmed & Algarni, 2018) conducted a study focusing on the weight reduction of the all-terrain vehicle (ATV) disk rotor while maintaining safety. Their research involved static structural and transient thermal analysis.The findings from these studies indicate that the design of the brake disc significantly affects its performance under heat. For instance, the study found that the brake disc with ridges had a stress level of 34Mpa, while the smooth and drilled objects had stress levels of 80Mpa and 57Mpa, respectively. This suggests that brake discs with grooves or ridges perform better than smooth or drilled ones due to their enhanced heat dissipation.

These studies collectively highlight the importance of considering both the structural and thermal aspects in the design of brake discs. They also underscore the need for further research to explore other design modifications that could enhance the performance of brake discs under different operating conditions.In the (Pranta et al., 2022), study on how to make the best brake disc with radial vanes by using a method called Taguchi design of experiments with consideration of important factors (Figure 2.3.5).

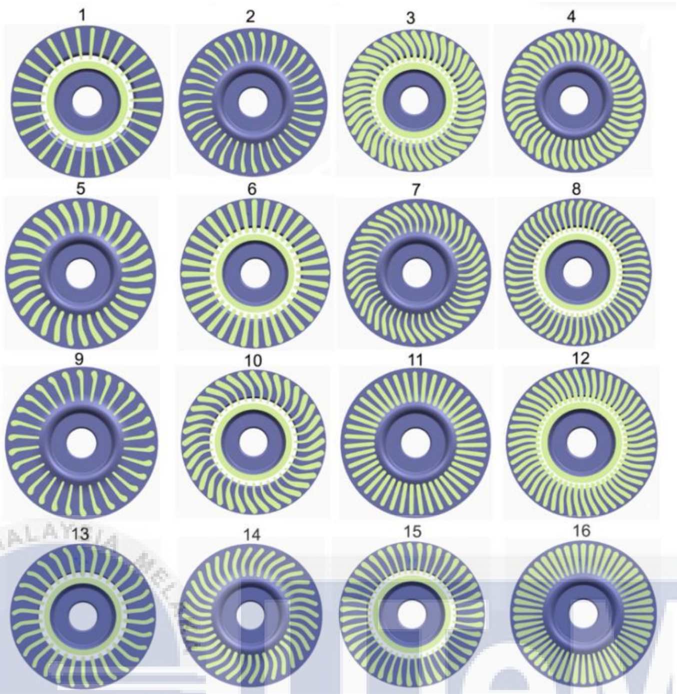


Fig. 4. Cross sectional view of the Taguchi L16 design for radial ventilated brake disc.

Figure 2.3.5 : Design of Radial Vane Disc Brake using Taguchi Design

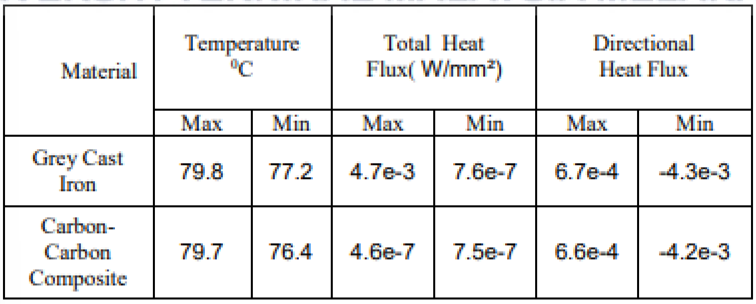
Through the FEM simulations, it has been observed that the width of the ventilation gap has a significant influence on the cooling of the brake disc. Increasing the ventilation gap from 8 mm to 14 mm results in a notable reduction in the cooling time of the disc, specifically by 21%. This indicates that a wider ventilation gap enhances the disc's ability to dissipate heat more efficiently. The findings emphasize the critical role of proper airflow within the brake system, as it directly impacts the cooling performance of the disc. By increasing the ventilation gap width, a larger volume of air can pass through, facilitating better heat transfer and faster cooling of the disc. This information can be valuable for designers and engineers seeking to optimize disc brake performance and mitigate issues related to overheating.

Generally, holes and airfoil vents in disc brakes enhance heat dissipation. During braking, the friction between the brake pads and rotor generates significant heat. By incorporating holes or airfoil vents, the surface area of the rotor increases, allowing for improved heat transfer. This helps to dissipate heat more effectively, reducing the risk of brake fade and maintaining consistent braking performance. Brake fade refers to the deterioration of braking performance due to excessive heat buildup. The enhanced heat dissipation provided by holes and airfoil vents helps to mitigate brake fade. By dissipating heat more efficiently, these features prevent the brake system from reaching critical temperatures that can lead to decreased stopping power and loss of control. Holes and airfoil vents also aid in water evacuation from the rotor surface. When driving in wet conditions, water can accumulate between the brake pads and rotor, leading to reduced friction and compromised braking performance. The presence of holes or airfoil vents allows water to escape through these channels, helping to maintain optimal pad-to-rotor contact and ensuring reliable braking even in wet weather. The design of holes and airfoil vents promotes better airflow around the brake rotor (Jafari & Akyüz, 2022). As the vehicle moves, these features facilitate the entry of air into the rotor and direct it across the surface, enhancing cooling efficiency. The increased airflow helps to carry away heat more effectively, preventing hot spots and ensuring consistent performance during demanding driving situations. The inclusion of holes and airfoil vents can reduce the weight of the brake rotor. By removing material from specific areas, the overall weight of the rotor is decreased. This reduction in unsprung mass contributes to improved handling, suspension response, and fuel efficiency, benefiting the overall performance of the vehicle. Holes and airfoil vents can create edges and contours on the rotor surface. These features improve the initial pad bite, enhancing the friction between the pads and rotor during the early stages of braking. The improved pad bite results in a more immediate and precise braking feel, allowing for better modulation and control.

In conclusion, the research on various forms of vented holes in disc brakes has highlighted their significance in improving brake performance. The studies have examined factors such as heat dissipation, temperature, distribution stress, and deformation to assess the effectiveness of different hole configurations.

2.5 Thermal Analysis

In study of disc brake, most researchers used whether steady-state thermal analysis or transient thermal analysis both of them in Ansys Workbench. Steady state thermal analysis is the braking conditions are assumed to be constant over time. For instance, a constant braking force is applied, leading to a constant amount of heat being generated. This heat is then dissipated through conduction, convection, and radiation. While transient thermal analysis study the effect of heat generated considers the change in braking conditions over time. For example, it can simulate a scenario where a vehicle is braking hard, causing a sudden increase in heat, followed by a period of cooling when the brakes are released. This allows for a more realistic simulation of real-world driving scenarios, where braking conditions can vary greatly. The goal is to understand how the brake system behaves under these constant conditions. (Thiruvengadam, n.d.) used steady-state thermal analysis to study the difference of thermal behaviour between Grey Cast Iron and Carbon-Carbon Composite disc brake rotor (Table 2.3.3). The temperature load of 22°C to 80°C on the front face in one seconds.



Material	Temperature °C		Total Heat Flux(W/mm²)		Directional Heat Flux	
	Max	Min	Max	Min	Max	Min
Grey Cast Iron	79.8	77.2	4.7e-3	7.6e-7	6.7e-4	-4.3e-3
Carbon-Carbon Composite	79.7	76.4	4.6e-7	7.5e-7	6.6e-4	-4.2e-3

Table 2.3.3 : Result of Steady-State Analysis from (Thiruvengadam, n.d.)

When comparing Grey Cast Iron and Carbon-Carbon Composite as materials for disc brakes, it's important to consider factors such as temperature, total heat flux, and directional heat flux. Both materials can withstand similar temperature ranges, which is crucial in disc brake applications due to the high temperatures generated from friction. However, Grey Cast Iron has a slightly higher maximum temperature (79.8°C) compared to Carbon-Carbon Composite (79.7°C), and Carbon-Carbon Composite has a slightly lower minimum temperature (76.4°C) compared to Grey Cast Iron (77.2°C).

In terms of total heat flux, Grey Cast Iron significantly outperforms Carbon-Carbon Composite (4.7e-3 W/mm² vs 4.6e-7 W/mm²), indicating a higher capacity for heat transfer. This is beneficial for disc brakes, where rapid heat dissipation is required to prevent overheating.

The directional heat flux, which refers to the ability to direct heat flow, is quite similar for both materials. However, Grey Cast Iron has a slightly higher maximum directional heat flux (6.7e-4 vs 6.6e-4), suggesting a marginally better ability to direct heat flow.

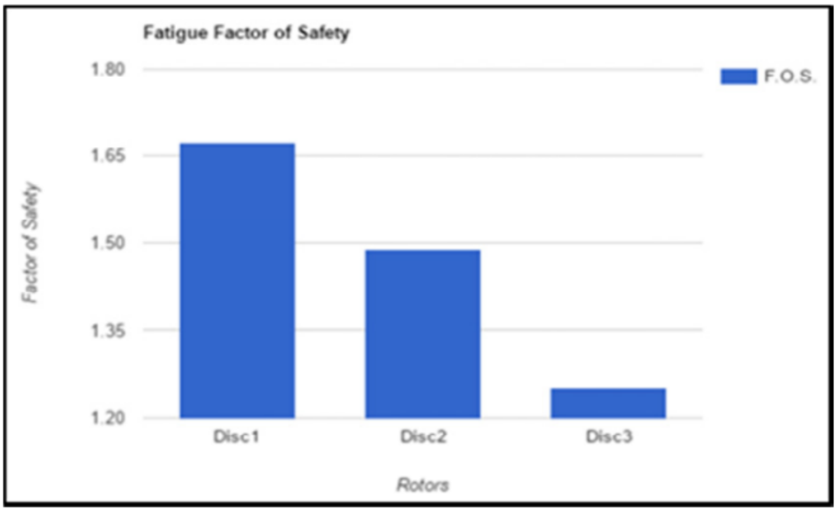
In conclusion, while both materials have their advantages, Grey Cast Iron appears to have a slight edge in terms of total heat flux and directional heat flux. However, the lower weight and higher temperature resistance of Carbon-Carbon Composite may make it a more suitable choice for certain applications.

(Dubale et al., 2021) study the thermal behaviour on 3 profile of disc brake rotors using transient thermal analysis to study the temperature distribution when the generated heat flux were varies over time during the 4 seconds of emergency braking condition. From the analysis, grooved disc brake rotor is better in distributing temperature than solid disc brake rotor and drilled disc brake rotor.

From these thermal analysis, we can conclude that steady-state analysis focus on study of thermal behaviour on disc brake with constant value of heat load applied while transient thermal analysis varies the heat load applied over time which is closer to real world braking condition.

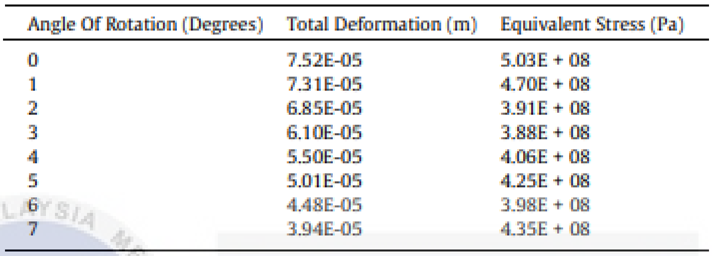
2.6 Structural Analysis

Structural analysis is a critical aspect of engineering that involves the evaluation of the effects of loads on physical structures and their components. This field has seen significant advancements with the advent of computational tools and information technologies, leading to the development of methods for sustainable and efficient design in engineering. Structural analysis can be broadly categorized into steady-state and transient structural analysis. Steady-state structural analysis deals with structures that are subjected to constant or periodic loads over an infinite time period. The response of the structure does not change over time. In the context of disc brakes, steady-state analysis can be used to evaluate the performance of the brake under constant or repetitive braking conditions (Reddy et al., n.d.). Transient analysis, on the other hand, deals with structures subjected to loads that vary with time. The response of the structure changes over time and the analysis aims to determine these changes. Transient analysis is particularly important due to the varying nature of the braking process. When brakes are applied, the kinetic energy of the vehicle is converted into heat, leading to a rise in temperature and thermal stresses in the brake disc. Transient analysis can help in understanding the thermo-elastic behaviour of the disc brake (Babukanth & Vimal Teja, 2012) under these varying conditions.



2.5.1 : Comparison of fatigue factor of safety (Karan Dhir, n.d.)

(Karan Dhir, n.d.) study the durability and fatigue factor of disc brake with 3 different designs. It is important to determine best disc brake rotor with long lifespan and resist fatigue cracks and deformation which lead to improvement of wear resistance of the material surface and reduction of braking noise (Li et al., 2020). From the table, disc 1 with the highest factor of safety is the best performance disc brake rotor.



Angle Of Rotation (Degrees)	Total Deformation (m)	Equivalent Stress (Pa)
0	7.52E-05	5.03E + 08
1	7.31E-05	4.70E + 08
2	6.85E-05	3.91E + 08
3	6.10E-05	3.88E + 08
4	5.50E-05	4.06E + 08
5	5.01E-05	4.25E + 08
6	4.48E-05	3.98E + 08
7	3.94E-05	4.35E + 08

Table 2.5.1 : Result of Structural Analysis (Choudhary et al., 2022)

(Choudhary et al., 2022) used the static structural analysis to find the deformation and stress distribution on disc brake when varying the angle of rotation of ventilated holes. Based on the table, disc brake rotor with 7 degree angle of rotation of ventilated holes is the best design with lowest deformation and considerable value of stress.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides a comprehensive overview of the methods and procedures employed in this study to accomplish its objectives. The phrase "research methodology" pertains to a systematic approach for addressing issues related to research. The methodology needs to be structured effectively to fulfill the purpose of this research. The organization of procedures facilitates the smooth execution of this research, provided that the arrangement aligns with the components in Chapter 1.

3.2 Research Design

A flowchart serves as a graphical representation of the various stages in a process arranged sequentially. It is a versatile method that can be tailored to suit a range of applications and can be utilized to delineate each step. It is a prevalent approach for process analysis and is considered a crucial tool for quality control. The flowchart depicted in Figure 3.2.1 outlines the steps to be followed during the research.

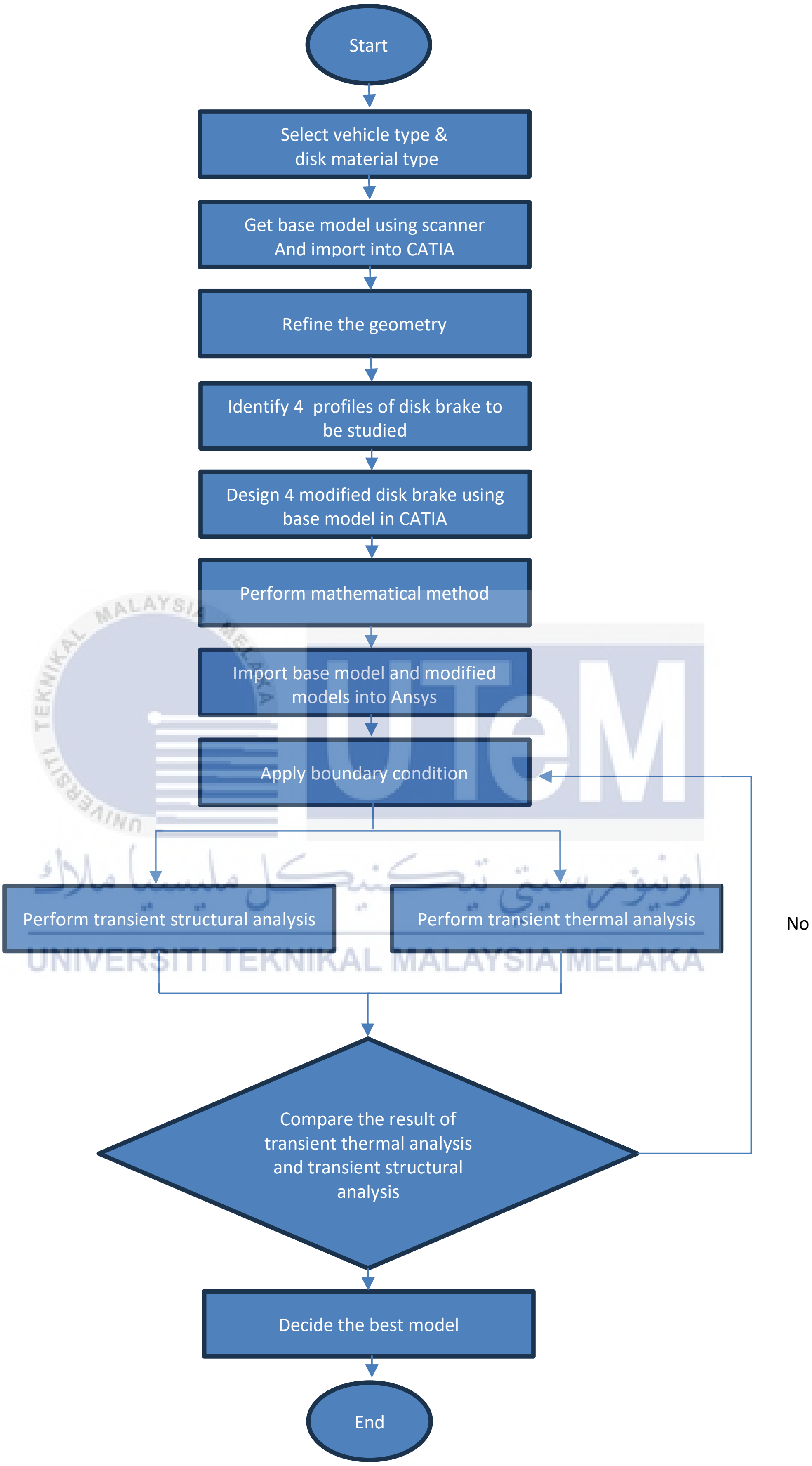


Figure 3.2.1 : Flowchart of Methodology

3.3 Design of Disc Rotor

Parameter name	**Parameter value (units)**
Outer diameter of disc rotor	288 mm
Inner diameter of disc rotor	135 mm
Hole diameter	68 mm
Drilled hole diameter	10 mm
Thickness of solid disc rotor	10 mm
Thickness of vented and vented with drilled holes disc rotors	25 mm
Vented thickness	10 mm

Table 3.3.1 : ISO standard dimensions of Audi A6 car

Based on the ISO standard disc brake rotor of Audi A6 car in Table 3.4.1, solid disk brake rotor and 4 profiles of disk brake rotor was developed. 3rd angle projection of developed models were inserted in appendices.

3.3.1 Model Base (refer figure 3.3.1.1) : Solid disc of Audi A6

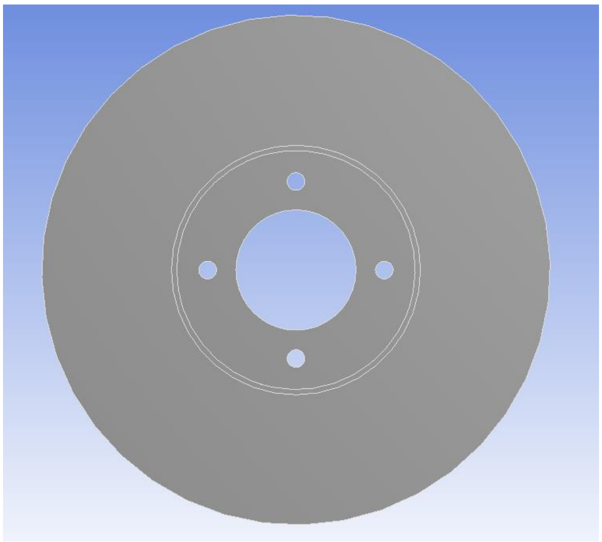


Figure 3.3.1.1: Model Base

3.3.2 Model Type 1 (refer figure 3.3.2.1) : Straight groove + Straight vent

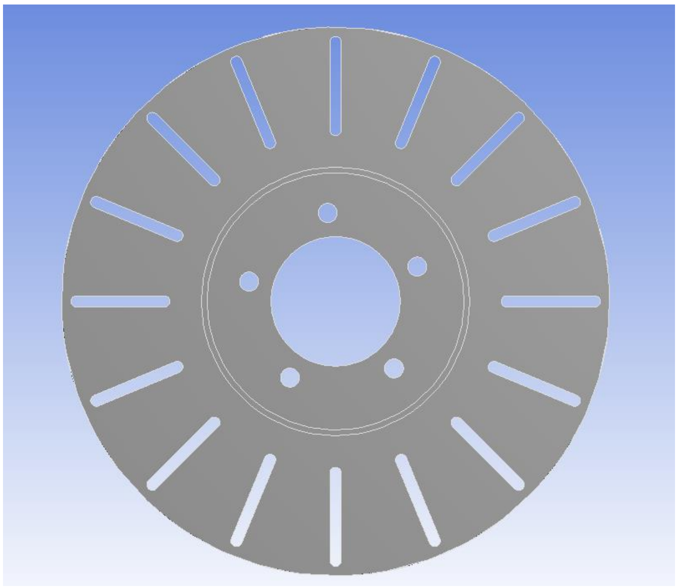


Figure 3.3.2.1 : Model Type 1

3.3.3 Model Type 2 (refer figure 3.3.3.1) : Curved groove + Curved Vent

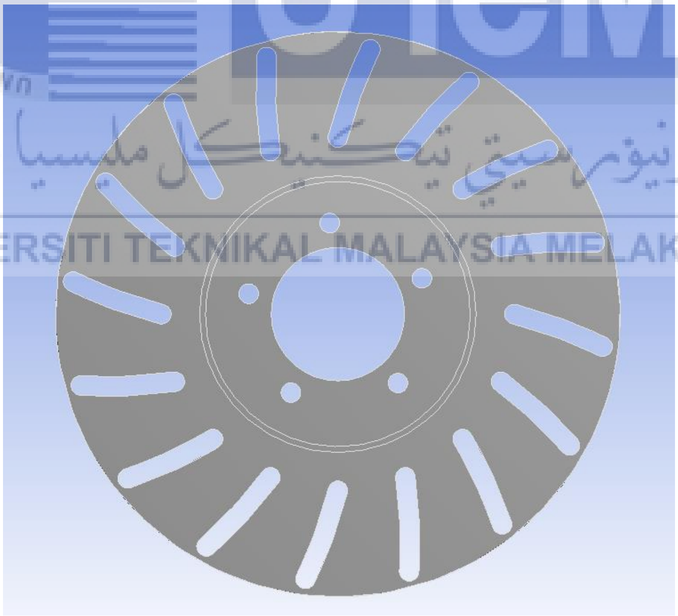


Figure 3.3.3.1: Model Type 2

3.3.4 Model Type 3 (refer figure 3.3.4.1) : 11^o curved groove + 11^o curved vent

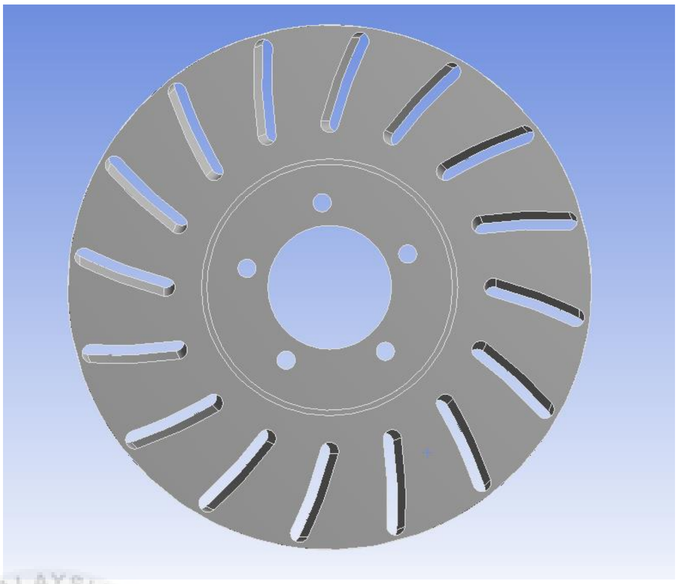


Figure 3.3.4.1: Model Type 3

3.3.5 Model Type 4 (refer figure 3.3.5.1) : 15^o curved groove + 15^o curved vent

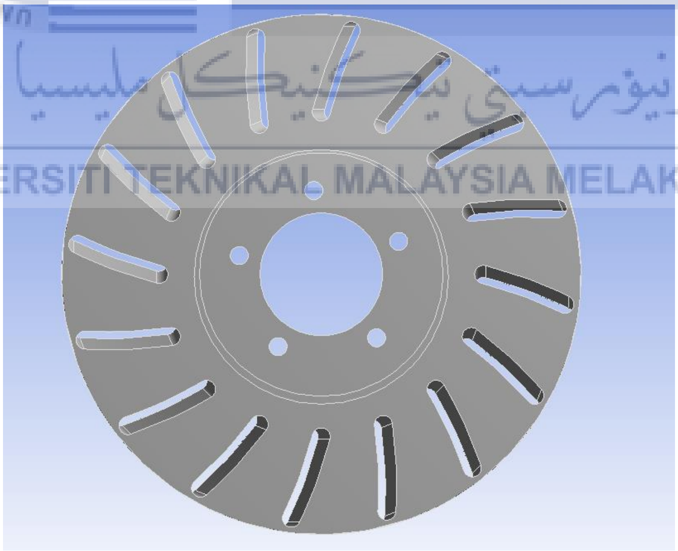


Figure 3.3.5.1: Model Type 4

15^{o} is the maximum modification we can develop due to interception between groove and ventilation pattern. In (10), show interesting result in modification of angle of rotation on drilled disc.

3.4 Material Selection

Material plays crucial part in disc brake rotor’s performance. From the perspective of engineers, development of performance of disc brake is top prior due to its influence in safety of the driver and passenger. However, the consideration of manufacturing cost need to be took place. Aluminium-Metal Matrix Composite (AMC) is superior than Grey Cast Iron (GCI) in term weight and thermal conductivity(*WCE2010_pp2322-2326*, n.d.). However, GCI seems to be more feasible material as it is economic and has good thermal conductivity although it is quite heavy(Kumar Jawahar, n.d.). So, material used for the disc brake is Grey Cast Iron (GCI). Figure 3.4.1 shows the material properties of Grey Cast Iron(Dubale et al., 2021).

Material properties	**Disc**
Thermal conductivity	57
Density	7250 kg/m3
Specific heat	460
Poisson’s ratio	0.28
Thermal expansion	10.85
Elastic Modulus E	138 Gpa
Tensile strength of disc ry (MPa)	206
Modulus of elasticity E of disc (GPa)	130
Compression to tensile strength ratio of disc	3.84
Brinell hardens of disc	220
Coefficient of friction m, between disk pad contact	0.35

Table 3.4.1 : Material properties of Grey Cast Iron

3.5 Mathematical Method

The mathematical properties was calculated using formula in (Dubale et al., 2021) and listed in Figure 3.5.1 with consideration of the parameter in Figure 3.5.2. Below is the calculation :

a. Thermal Effusivity

$$\xi = \sqrt{\mathrm{k}\rho C}$$

The value of ξ_p and ξ_p are assumed same as the journal in (Dubale et al., 2021) because the value use in calculation is considered same as used in the analysis.

b. Friction contact surface

For pad,

$$\mathrm{S}_p = \varphi_0 \int_{r_1}^{r_2} r dr = \frac{\varphi_0}{2}(r_2^2 - r_1^2) = \frac{65^0}{2}(0.144^2 - 0.0705^2) = 0.007883\, m^2$$

For disc,

$$\mathrm{S}_d = 2\pi \int_{r_1}^{r_2} r dr = 2\pi(r_2^2 - r_1^2) = 2\pi\,(0.144^2 - 0.0705^2) = 0.04953\, m^2$$

c. Partition Coefficient

$$\varpi = \frac{\xi_d \mathrm{S}_d}{\xi_d \mathrm{S}_d + \xi_p \mathrm{S}_p} = \frac{13787.49 * 0.04953}{13787.49 * 0.04953 + 2645.75 * 0.007883} = 0.97$$

d. Heat Flux on Disc

$$q_2(r,t) = q_{0_2}(r) * \left(1 - \frac{t}{t_b}\right) = \frac{\emptyset_0}{2\pi}\mu\varpi P_{max} r_4 \omega_0 \left(1 - \frac{t}{t_b}\right)$$

$$\omega_0 = \frac{v}{r} = \frac{30.56}{0.8318/2} = 73.479$$

$$q_2(r,t) = \frac{65^0}{2} * 0.35 * 0.97 * 1.3 * 10^6 * 0.144 * 73.479 * \left(1 - \frac{t}{4}\right)$$

$$q_2(r,t) = 0.74324 * 10^6 * \left(1 - \frac{t}{4}\right)$$

3.6 Boundary Condition

The distribution of pressure from heat generation was due to friction, the heat flux on the surface, the distribution of temperature in relation to braking time, the radial temperature distribution on the surface, and the thermal effect stress. Based on (Dubale et al., 2021) following assumptions have been made:

1.All kinetic energy at the disc brake surface is transformed into heat flux or frictional heat.

2. The heat transfer in this analysis occurs only through conduction and convection. Heat transfer by radiation can be disregarded as it only accounts for 5% to 10%.

3. Material properties are isotropic and do not depend on temperature.

4. The rate of heat produced through friction equals the friction power. A portion of the frictional heat is absorbed by the disc, and the rest is absorbed by the pads.

5. If it is assumed that all of the friction power is converted into thermal energy, the heat partition coefficient is given by the parameter. The thermal energy generated at the brake friction interface can be transferred to both the brake and the pads.

Thermal Effusivity of Disc, ξ_d	13787.49 Ws^1/2m^2K
Thermal Effusivity of Pad, ξ_p	2645.75 Ws^1/2m^2K
Disc Friction Contact Surface, S_d	0.04953 m^2
Pad Friction Contact Surface, S_p	0.00788 m^2
Heat Flux on Disc, q_2	0.74324*10^6 (1-t/4)
Partition Coefficient, ϖ	0.97

Table 3.5.1 : Mathematical Properties

Mass of the Vehicle, m_v	1600 kg
Initial Velocity,v_0	110km/h

Rim Diameter,D_r	431.8 mm
Wheel Diameter, D_w	831.8 mm
Inner Radius of Pad	0.0705 m
Outer Radius of Pad	0.1440 m
Braking Time,t_b	4 seconds
Max Pressure	1.3 Mpa

Table 3.5.2 : Parameter of Audi A6

Based on the formula presented in chapter 2.2.1 which was refered from [(Dubale et al., 2021)

Convective Heat Transfer Coefficient	230 W/m^2◦C
Initial Temperature	22◦C

Table 3.5.3 : Boundary Condition

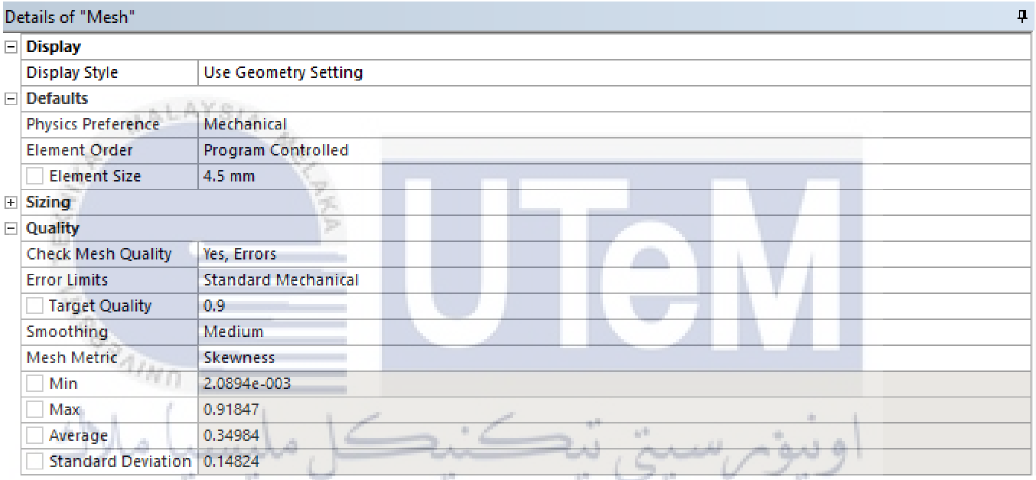
Meanwhile Figure 3.5.3 provides the specifics of the boundary condition that is applied in all following simulations.

3.7 Meshing

In this research, the tetrahedrons method is utilized in the meshing process to generate an effective mesh for the simulation. The tetrahedral element is advantageous as it is compatible with most meshing techniques, especially for complex structures with realistic geometry like disc brakes (Oberst et al., 2013). To assess the quality of the final mesh, a mesh quality control is implemented. This control uses the skewness method to evaluate the performance of the mesh. The skewness measures how closely a face or cell approximates the ideal shape, such as equilateral or equiangular. Figure 3.6.1 and Figure 3.6.2 provide an in-depth view of the mesh configuration and the criteria for mesh formation. In Figure 3.6.2, the maximum skewness is 0.918, which falls within the acceptable range. All simulations also employ an element size of 4.5 mm as it provides a decent level of independent mesh and allows for manageable computation time.

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Order	Use Global Setting

Table 3.6.1 : Meshing Method



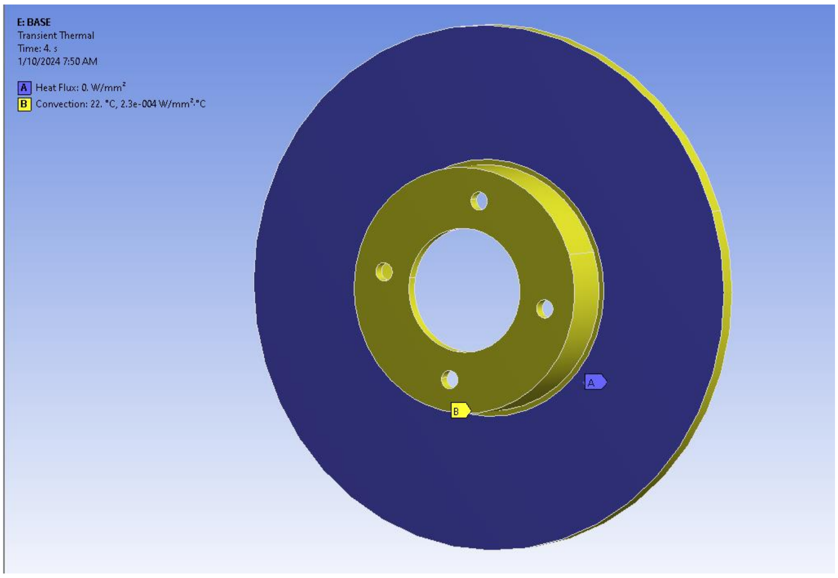
Details of "Mesh"

⊟ **Display**	
Display Style	Use Geometry Setting
⊟ **Defaults**	
Physics Preference	Mechanical
Element Order	Program Controlled
☐ Element Size	4.5 mm
⊞ **Sizing**	
⊟ **Quality**	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
☐ Target Quality	0.9
Smoothing	Medium
Mesh Metric	Skewness
☐ Min	2.0894e-003
☐ Max	0.91847
☐ Average	0.34984
☐ Standard Deviation	0.14824

Figure 3.6.2 : Meshing Setting

3.8 Transient Thermal Analysis

The transient thermal analysis determines the temperature and other thermal quantities that vary over time.



E: BASE
Transient Thermal
Time: 4. s
1/10/2024 7:50 AM

A Heat Flux: 0. W/mm²
B Convection: 22. °C, 2.3e-004 W/mm²·°C

Figure 3.7.1 : Convection and Heat Flux Applied

The primary goal of conducting a transient thermal analysis of a disc rotor is to assess the rotor’s performance under intense braking conditions. In this research, the braking condition is in emergency braking for 4 seconds. 0.74324*10^6 (1-t/4) of heat flux was applied on both side of disc brake rotor and only convection with value 230 W/m^2◦C applied on all surface except the surface where heat flux was applied. From the result we can analyse the heat generation and dissipation, material analysis for selecting suitable materials for the disc rotor, understanding the distribution of thermal and structural stress on the brake rotor under real-time conditions, and evaluating the overall braking performance and safety of the disc brake design.

3.9 Transient Structural Analysis

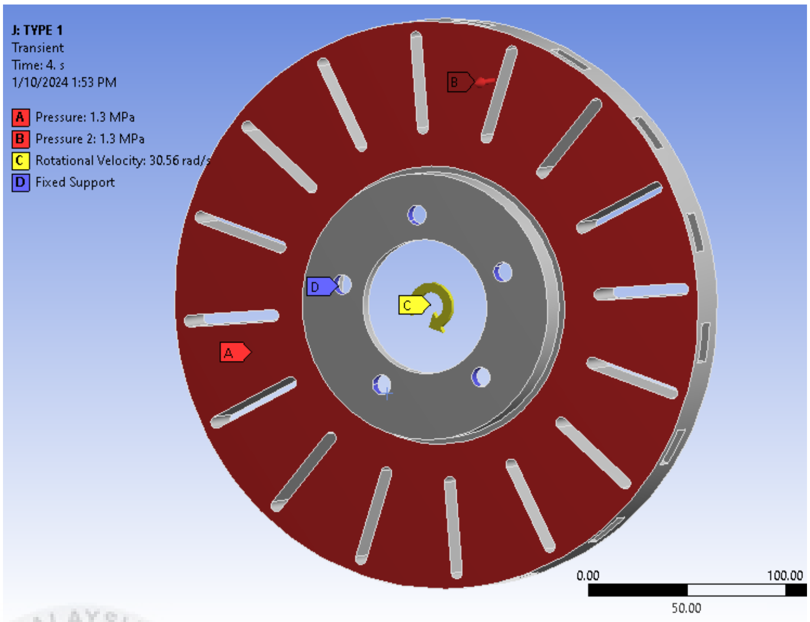


Figure 3.8.1 : Pressure, Rotational Velocity and Fixed Support Applied

This analysis provide valuable insights into the distribution of stress during braking. It involves a detailed examination of stress distribution, material analysis for selecting suitable materials for the disc rotor, and evaluating the overall braking performance and safety of the disc brake design. Although the structural analysis is not the main objective of the research, it still need to be analyze because it is the key to determine whether the design is feasible which is able to withstand pressure in a long duration in other word, its resistance and life span. For the simulation, the pressure applied on both side of disc brake rotor. Then fixed support applied to the 5 holes and rotational velocity applied for 30.56 rad/s. Then, the result being analyzed focus on its structural deformation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and analysis on transient thermal analysis and thermo-structural coupled analysis of a solid disc and 4 new customized design of Audi A6’s disc brake rotor.

4.2 Results

The disc brake undergo 2 analysis which were transient thermal analysis and transient structural analysis.

4.2.1 Transient Thermal Analysis

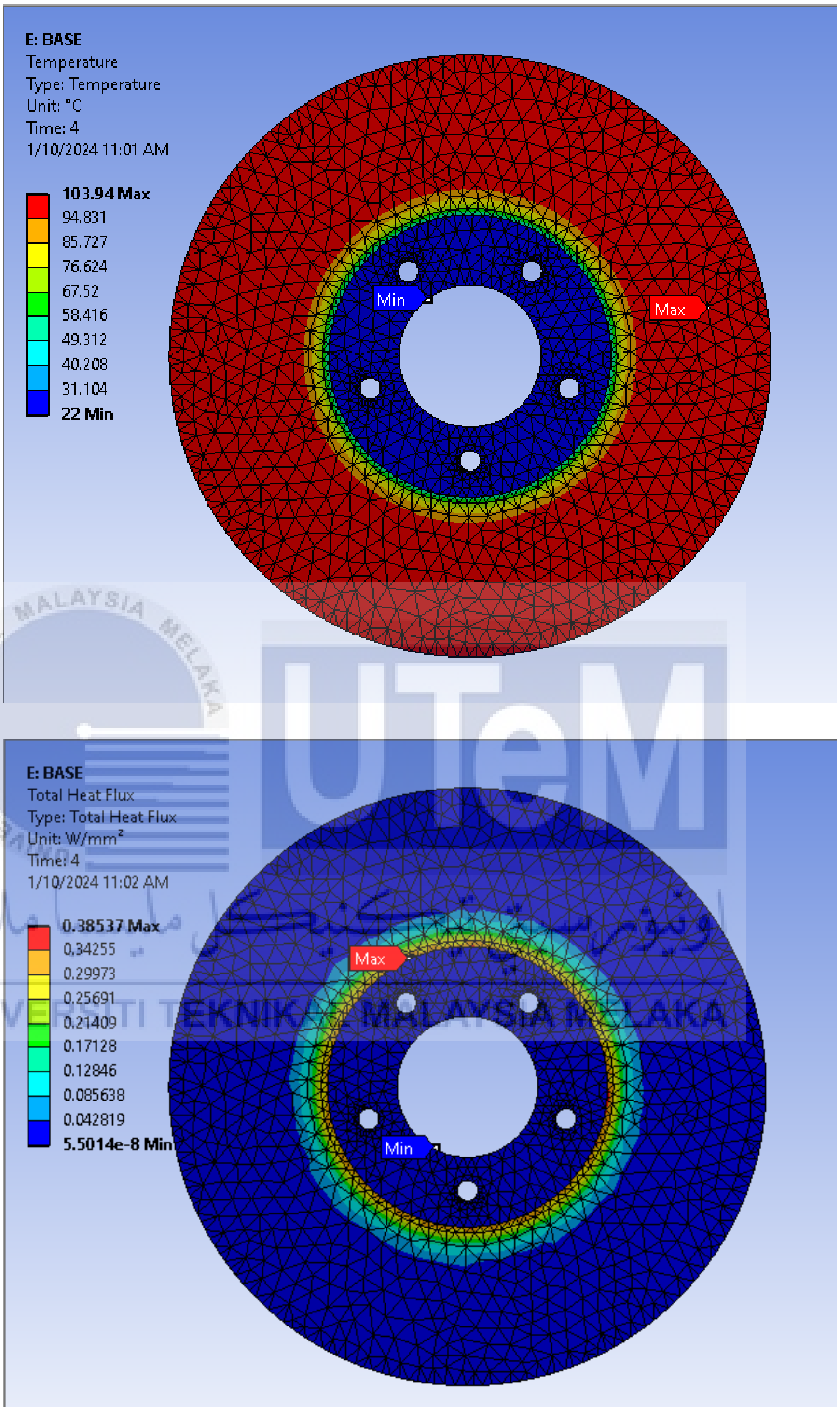


Figure 4.2.1.1 : Result of Base Model (Thermal)

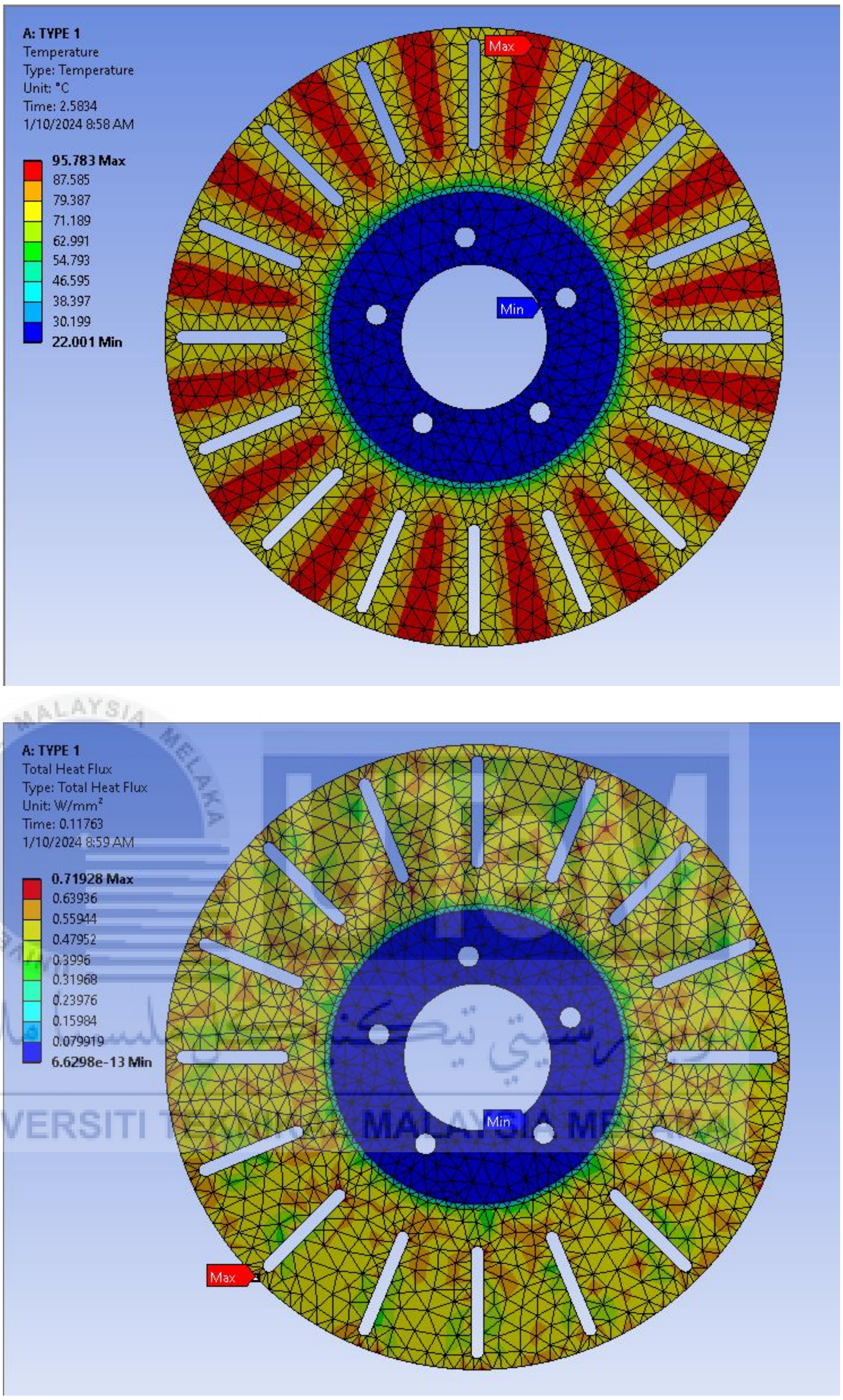


Figure 4.2.1.2 : Result of Type 1 (Thermal)

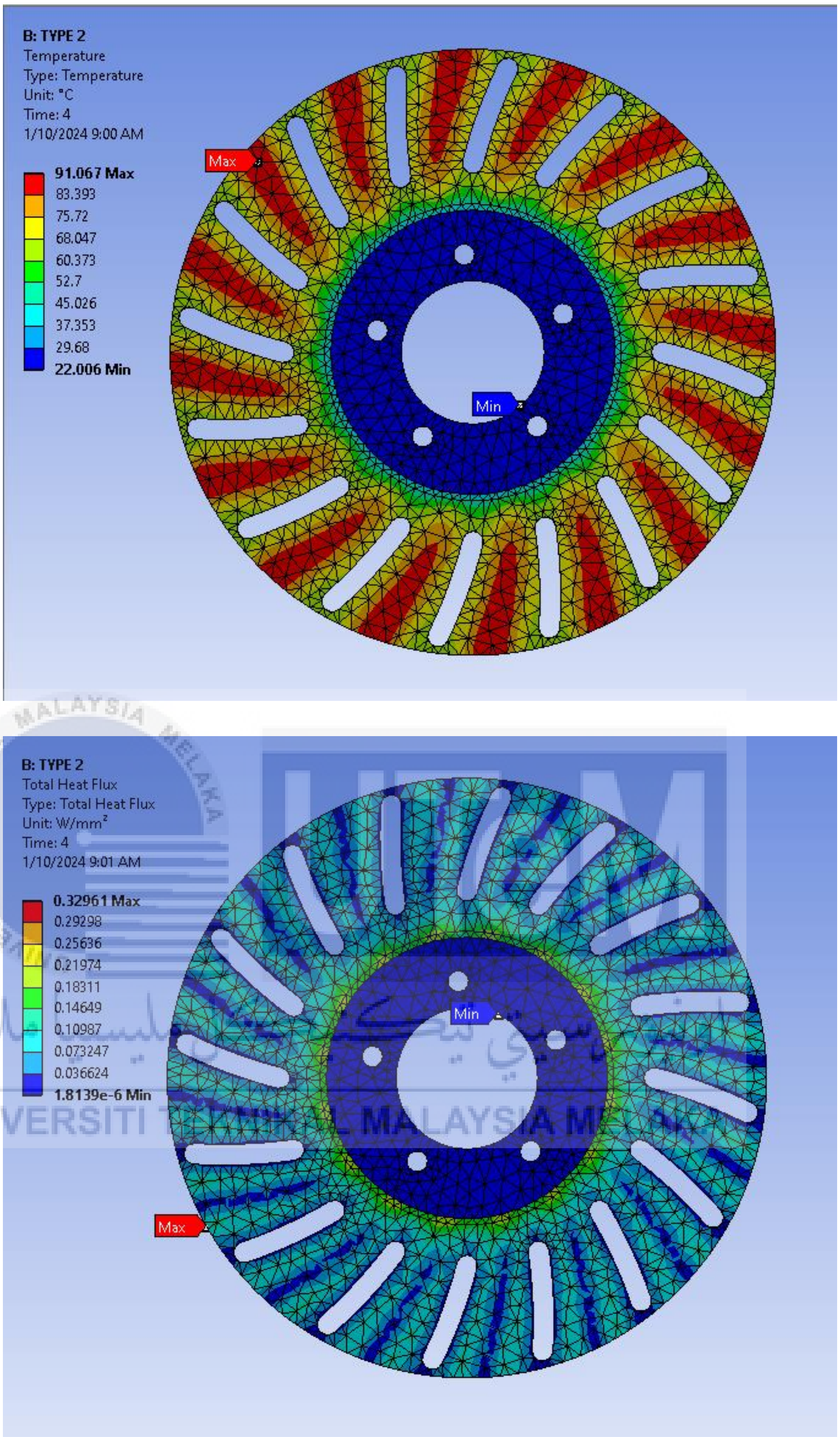


Figure 4.2.1.3 : Result of Type 2 (Thermal)

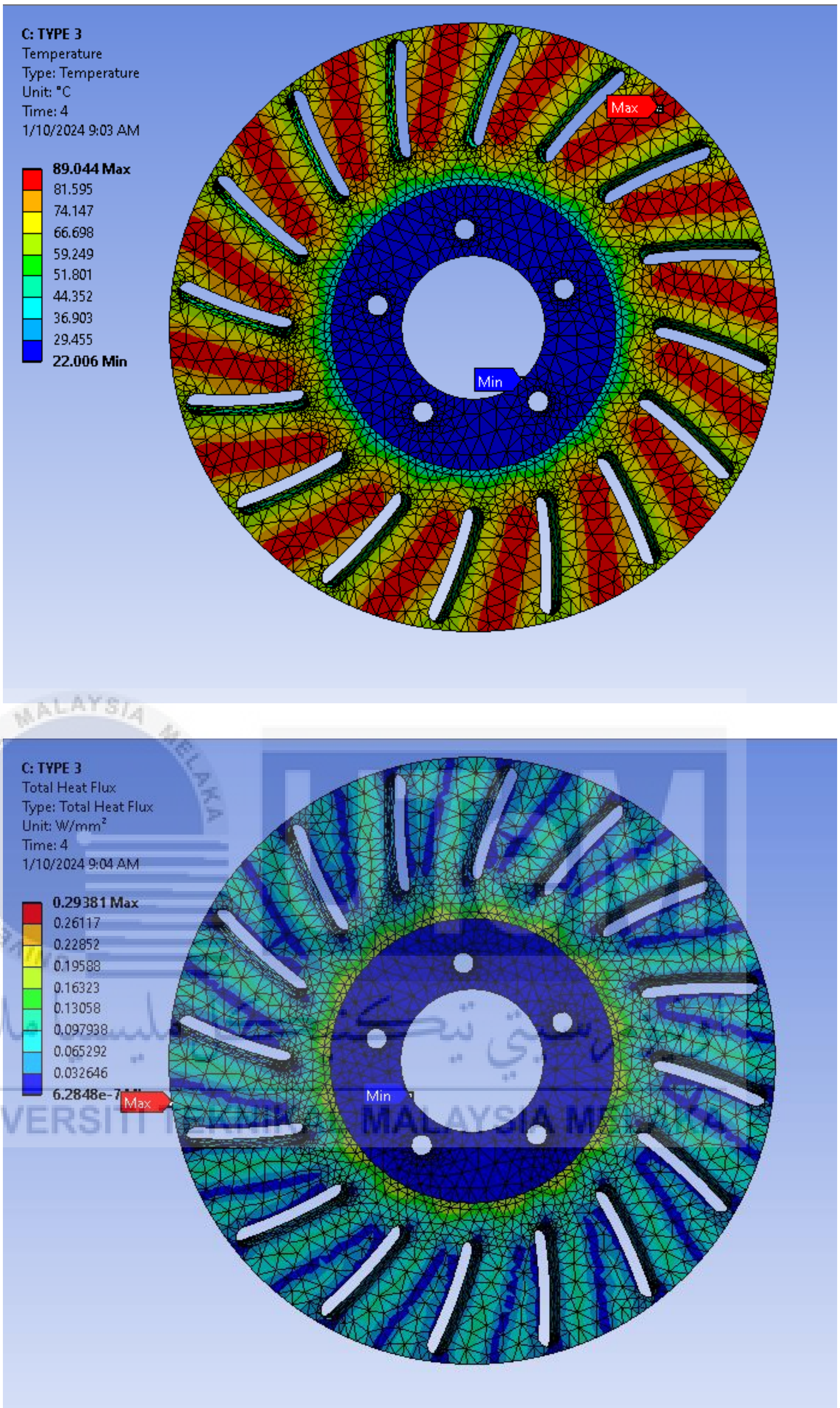


Figure 4.2.1.4 : Result of Type 3 (Thermal)

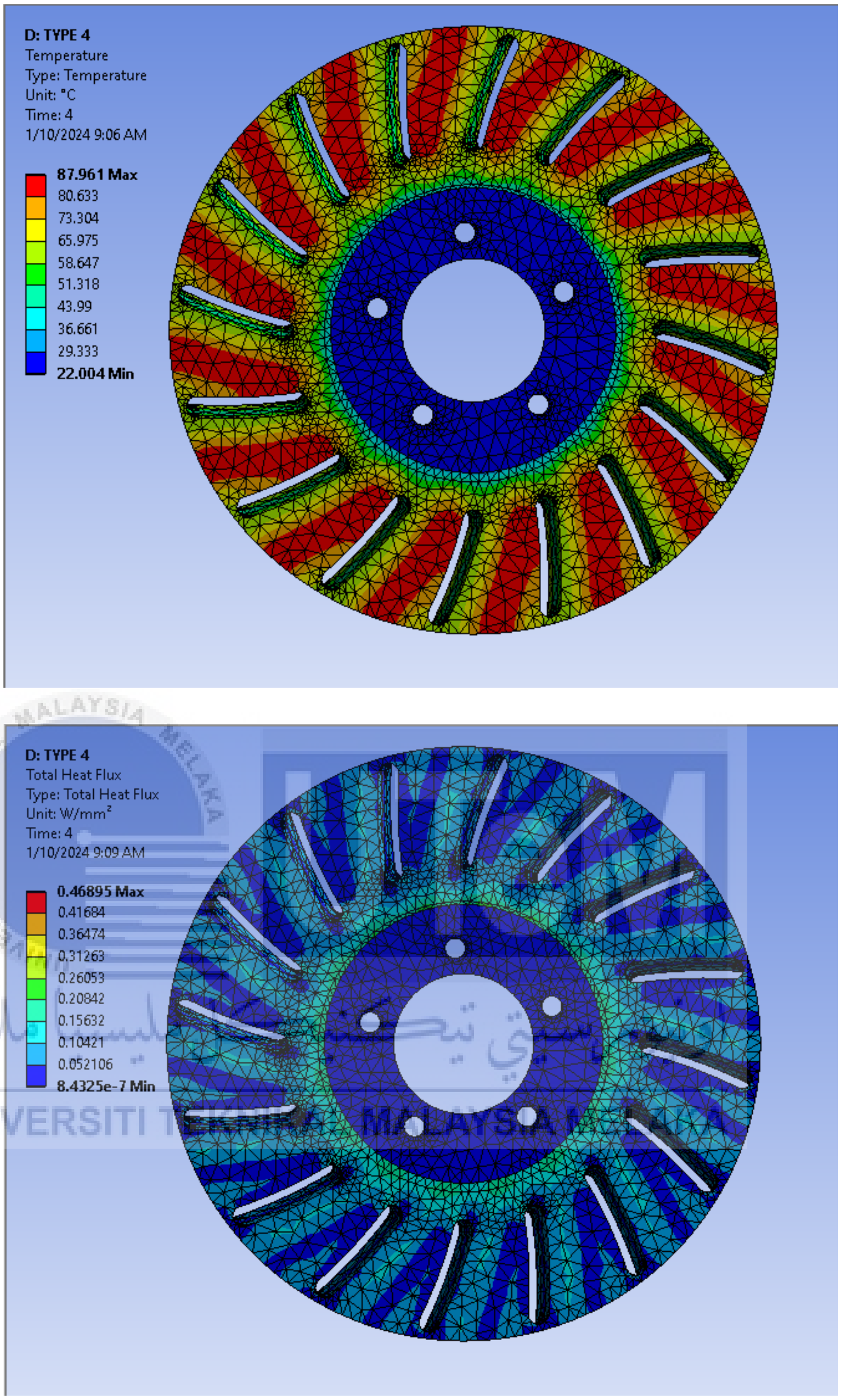


Figure 4.2.1.5 : Result of Type 4 (Thermal)

4.2.2 Transient Structural Analysis

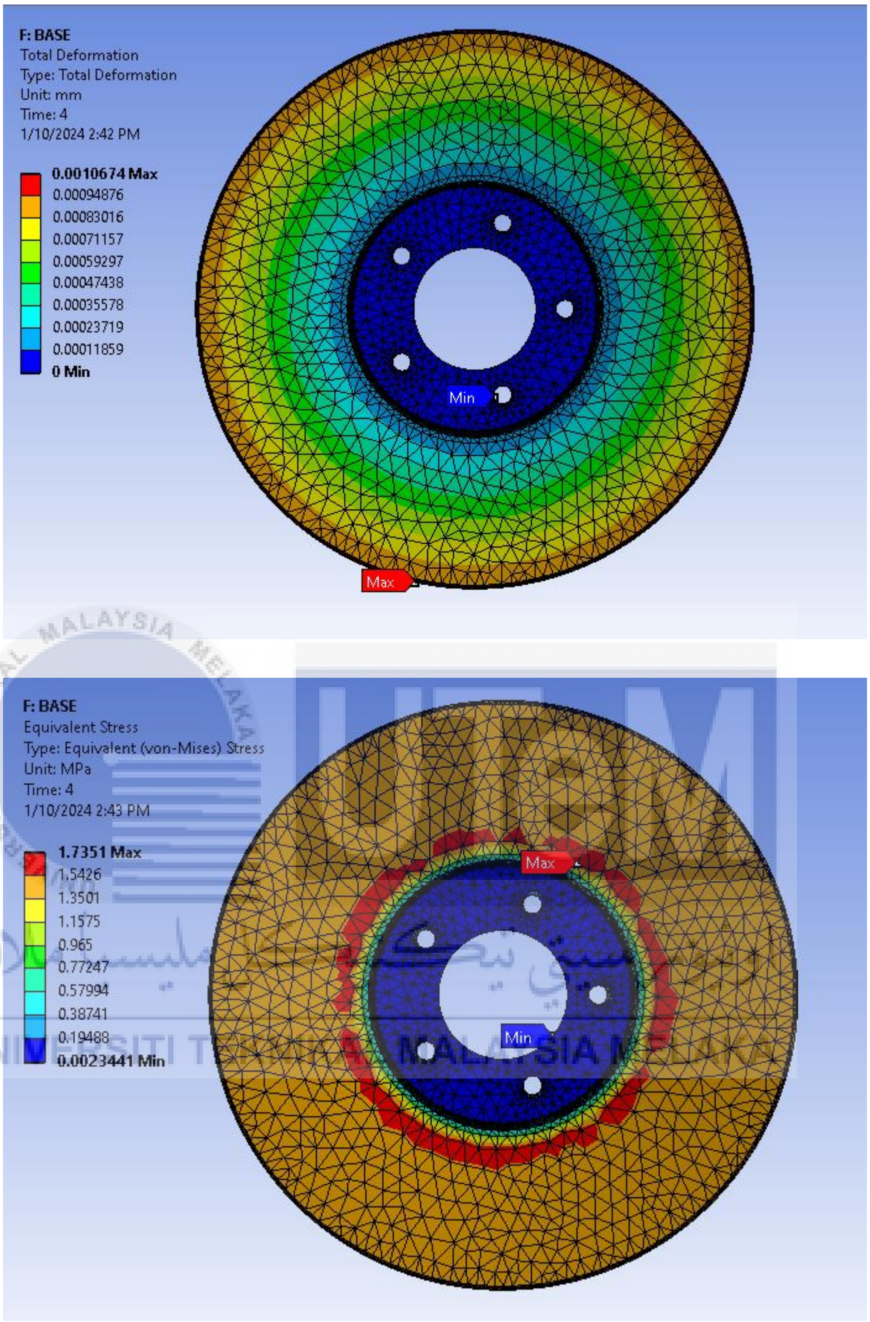


Figure 4.2.2.1 : Result of Base (Structural)

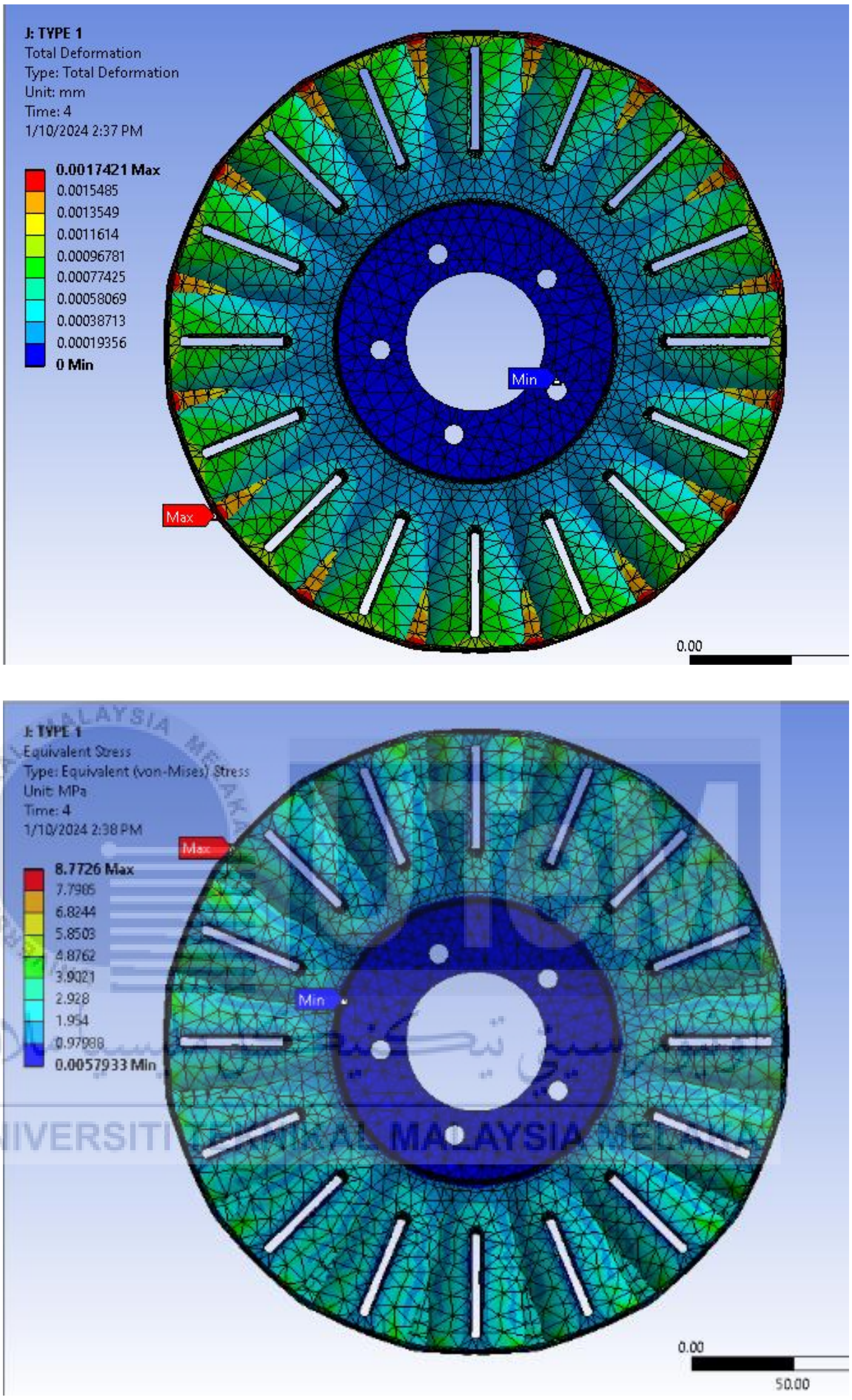
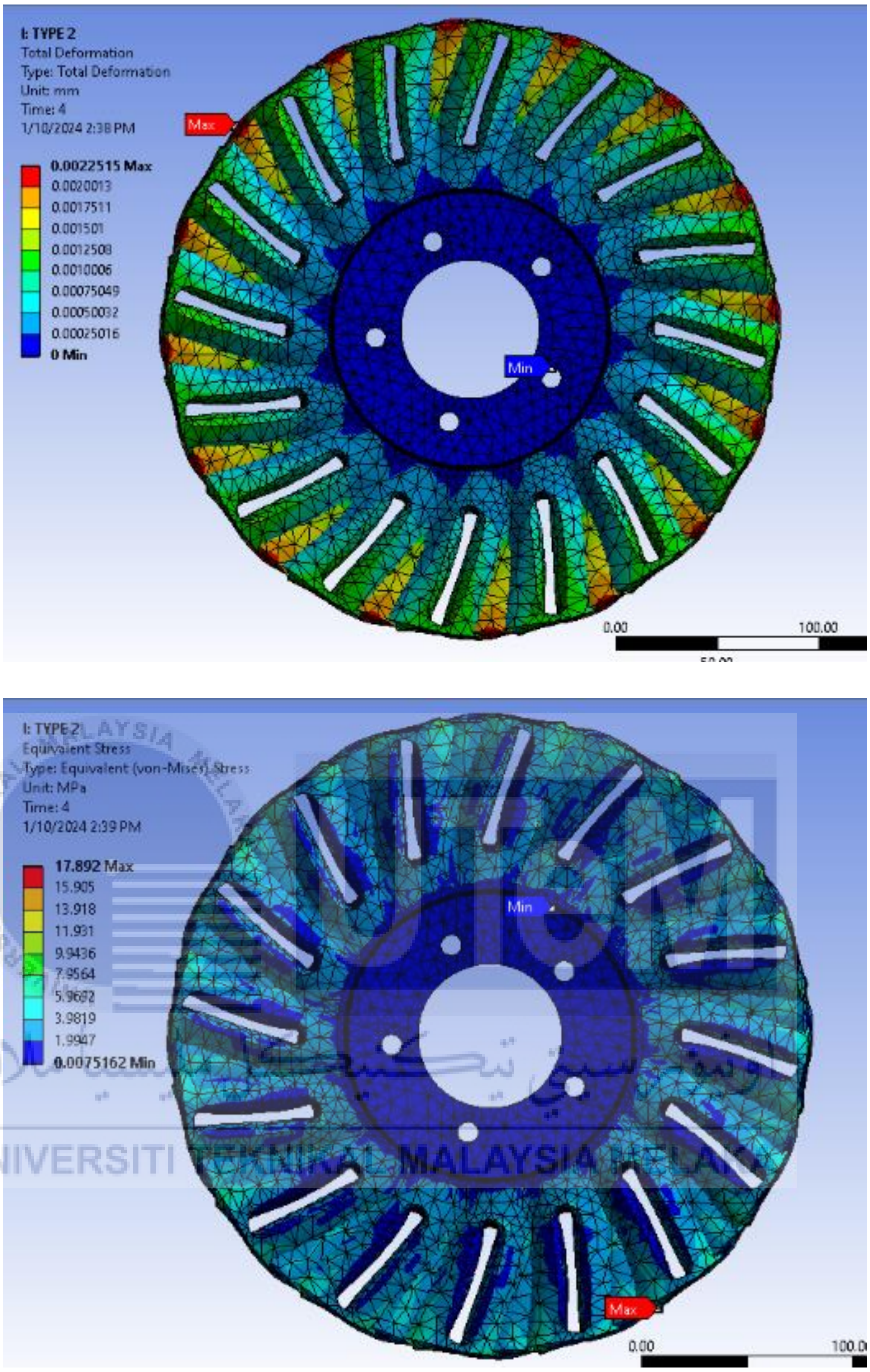


Figure 4.2.2.2 : Result of Type 1 (Structural)



I: TYPE 2
Total Deformation
Type: Total Deformation
Unit: mm
Time: 4
1/10/2024 2:38 PM

I: TYPE 2
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 4
1/10/2024 2:39 PM

Figure 4.2.2.3 : Result of Type 2 (Structural)

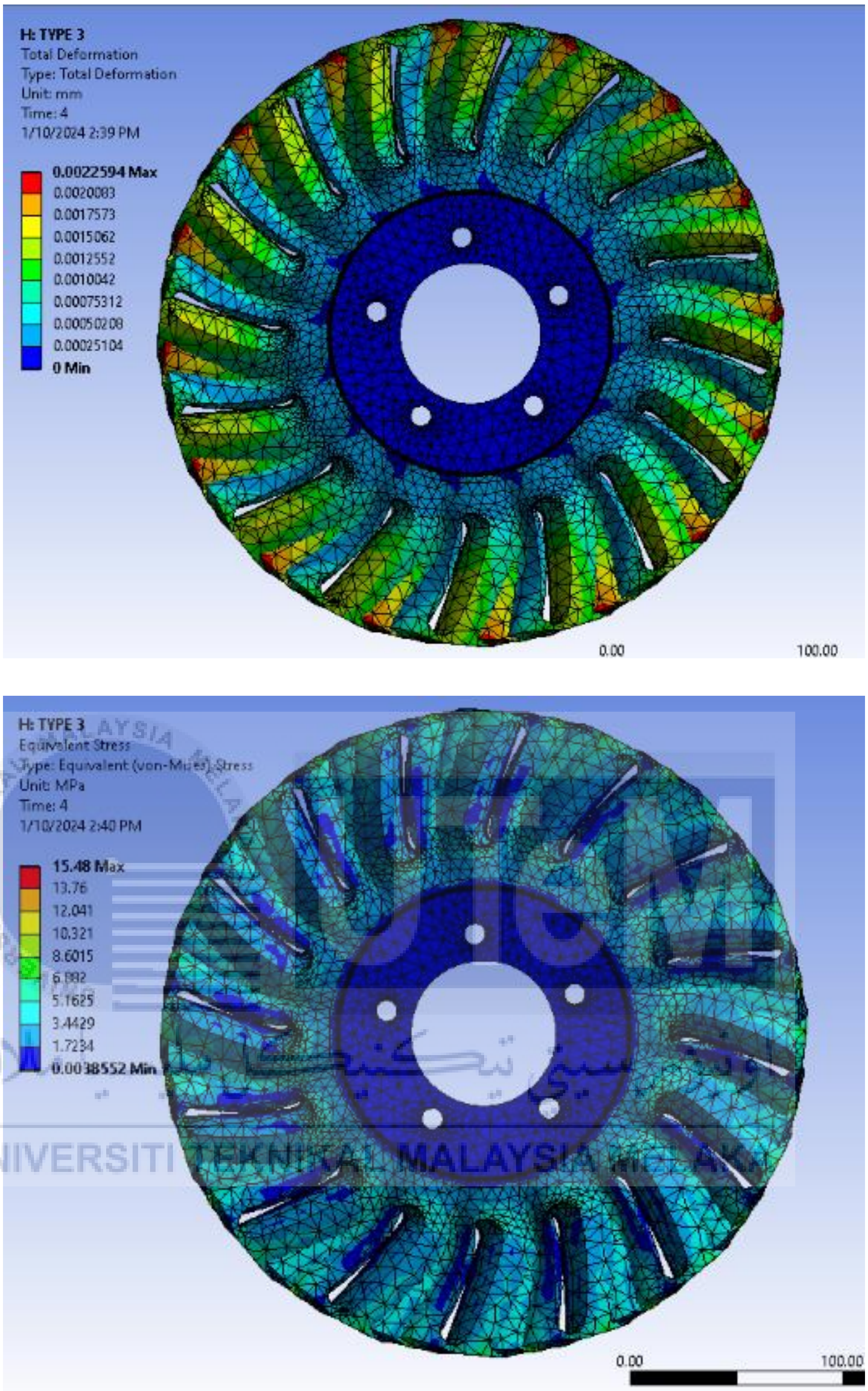


Figure 4.2.2.4 : Result of Type 3 (Structural)

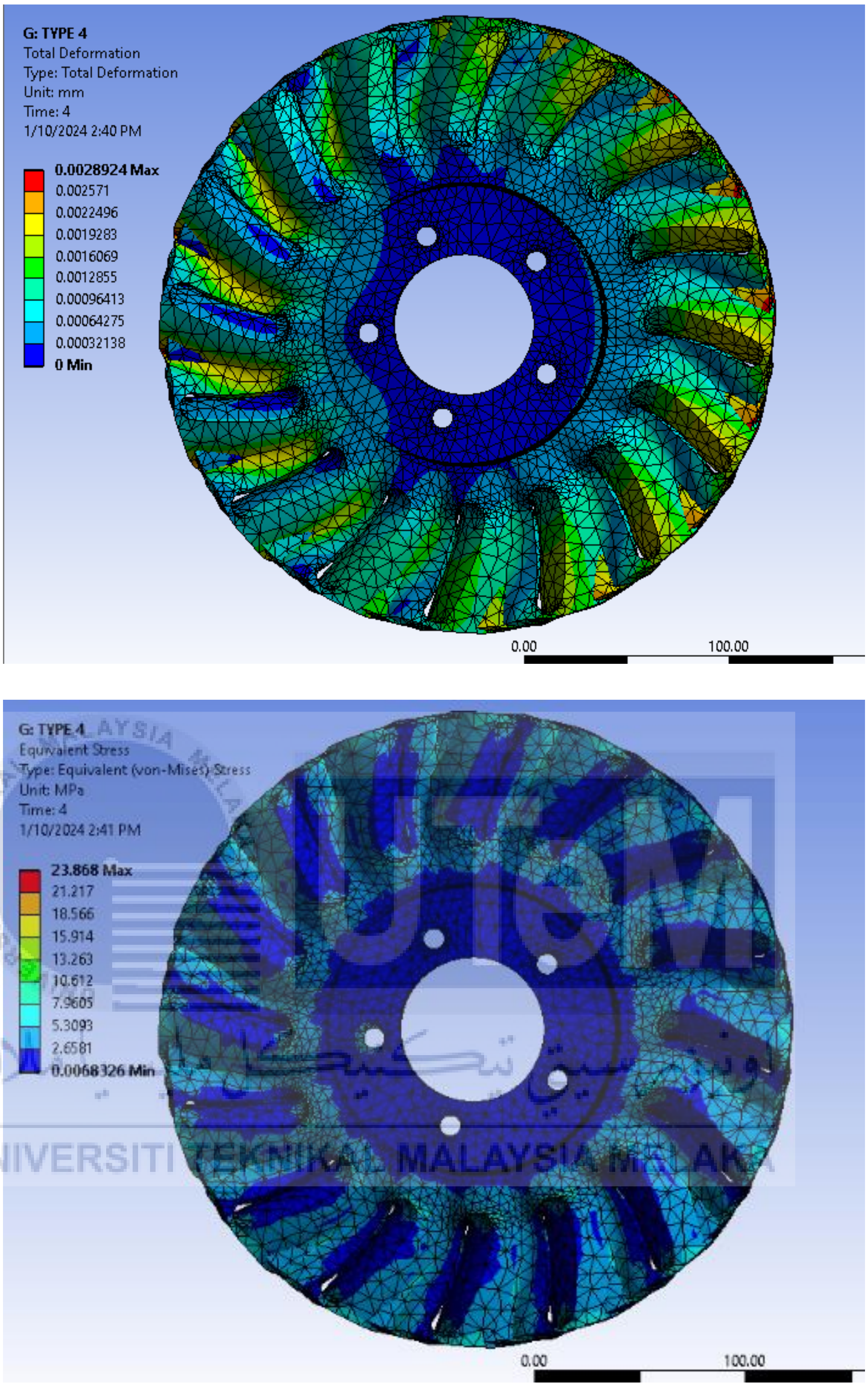


Figure 4.2.2.5 : Result of Type 4 (Structural)

4.3 Discussion

Following the analysis results, tables are created to represent the properties. Additionally, graphs are drawn to illustrate the variations in temperature, total heat flux, total deformation and equivalent stress with different disc brake designs.

MODEL	MAX TEMPERATURE (°C)	TOTAL HEAT FLUX (W/mm^2)	TOTAL DEFORMATION (mm)	EQUIVALENT STRESS (Mpa)
BASE	100.72	0.36787	1.07E-03	1.7351
TYPE 1	93.403	0.64087	1.74E-03	8.7726
TYPE 2	88.15	0.31463	2.25E-03	17.892
TYPE 3	86.229	0.28057	2.26E-03	15.48
TYPE 4	84.899	0.44535	2.89E-03	23.868

Table 4.3.1 : Result of Transient Thermal and Transient Structural Analysis

TIME	MAX TEMPERATURE				
	BASE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
0	0	0	0	0	0
5.00E-01	58.367	57.673	57.745	60.384	62.601
1.00E+00	74.531	73.428	73.708	75.575	78.735
1.5	86.261	83.728	84.491	84.317	88.207
2	94.858	90.264	91.562	90.09	93.389
2.5	100.53	93.407	95.283	93.568	95.144
3	103.38	93.379	95.868	93.993	94.014
3.5	103.45	90.376	93.451	91.502	90.322

4	100.72	84.582	88.15	86.229	84.899

Table 4.3.2 : Result of Max Temperature over Time

TIME	TOTAL HEAT FLUX				
	BASE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
0	0	0	0	0	0
5.00E-01	0.64444	0.64087	0.64468	0.66367	0.69217
1.00E+00	0.59494	0.59308	0.59119	0.59071	0.68285
1.5	0.57482	0.54433	0.54568	0.54835	0.63365
2	0.53658	0.47866	0.49614	0.49071	0.56162
2.5	0.48735	0.41384	0.43465	0.42901	0.58222
3	0.42982	0.34719	0.39883	0.35574	0.56504
3.5	0.38372	0.30106	0.36525	0.32477	0.51753
4	0.36787	0.25294	0.31463	0.28057	0.44535

Table 4.3.3 : Result of Heat Flux over Time

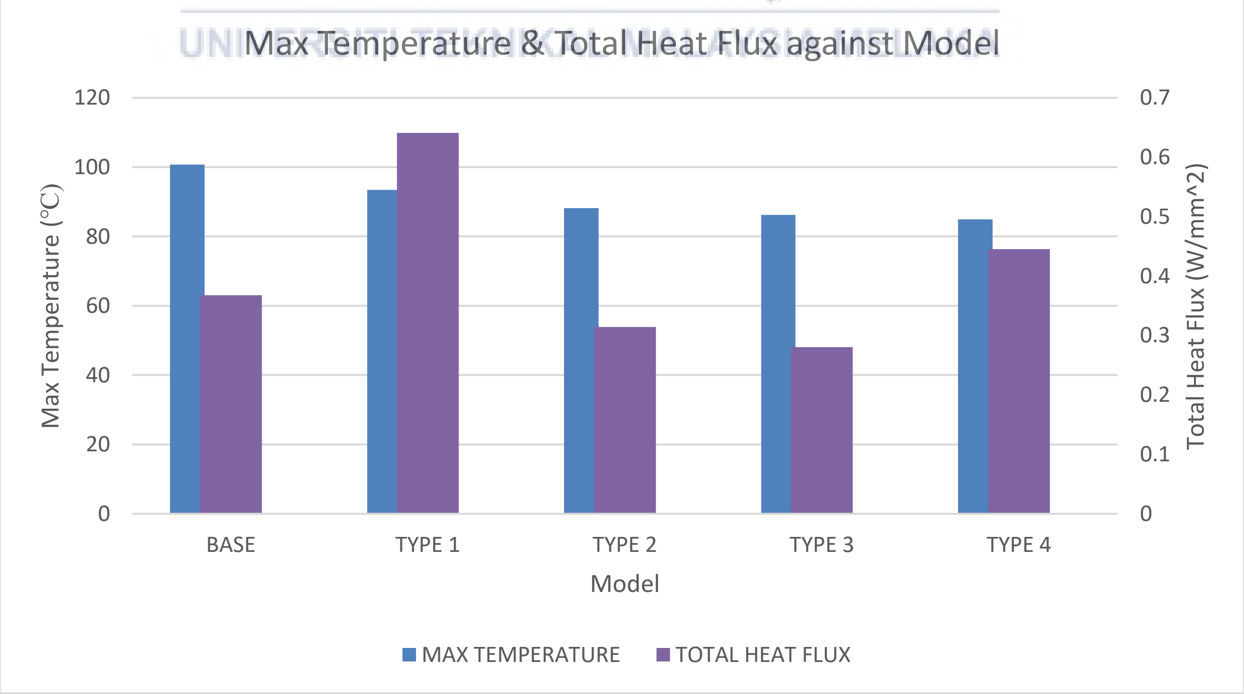


Figure 4.3.1 : Bar Graph Max Temperature & Total Heat Flux against Model

Based on Table 4.3.1 it is clear that Model Type 4 has lowest temperature which is 84.899℃ generated on the disc brake while Model Type 1 has the highest temperature generated, 93.403℃. The difference is 8.504℃. By comparing to the Model Base, Model Type 4 achieved 15.71% improvement while Model Type 1 only achieved 7.26% improvement.). This implies that Type 4, with its 15-degree curved groove and vent, might have a more efficient heat distribution system, possibly due to its design.

Conversely, total heat flux is associated with the rate of heat dissipation from the brake disc to the surrounding environment. A higher heat flux implies more effective heat dissipation. In term of heat flux, Model Type 3 has lowest total heat flux value, 0.28057 W/mm^2 and Model Type 1 has highest total heat flux value, 0.64087 W/mm^2. The difference is 0.3603 W/mm^2. By comparing with Model Base, Model Type 3 achieved 23.73% improvement while Model Type 1 has lower performance than Model Base in term of total heat flux generation. As the disc brake rotors made of same material which is gray cast iron, this could be influenced by or the surface area available for heat dissipation.

The design of the grooves and vents in disc brakes plays a significant role in heat distribution and dissipation. The grooves and vents increase the surface area of the disc brake, enhancing heat dissipation. Moreover, the design of the grooves and vents affects the airflow around the disc brake. Proper airflow is essential for carrying away the heat generated during braking. The grooves and vents facilitate airflow, helping to cool the disc brake more efficiently. The curved design of the grooves and vents in Types 2, 3, and 4 may allow for better airflow compared to the straight design in Type 1, potentially explaining their lower maximum temperatures.

In conclusion, the design of the grooves and vents in disc brakes, which influences the surface area and airflow, is a critical factor in heat distribution and dissipation.

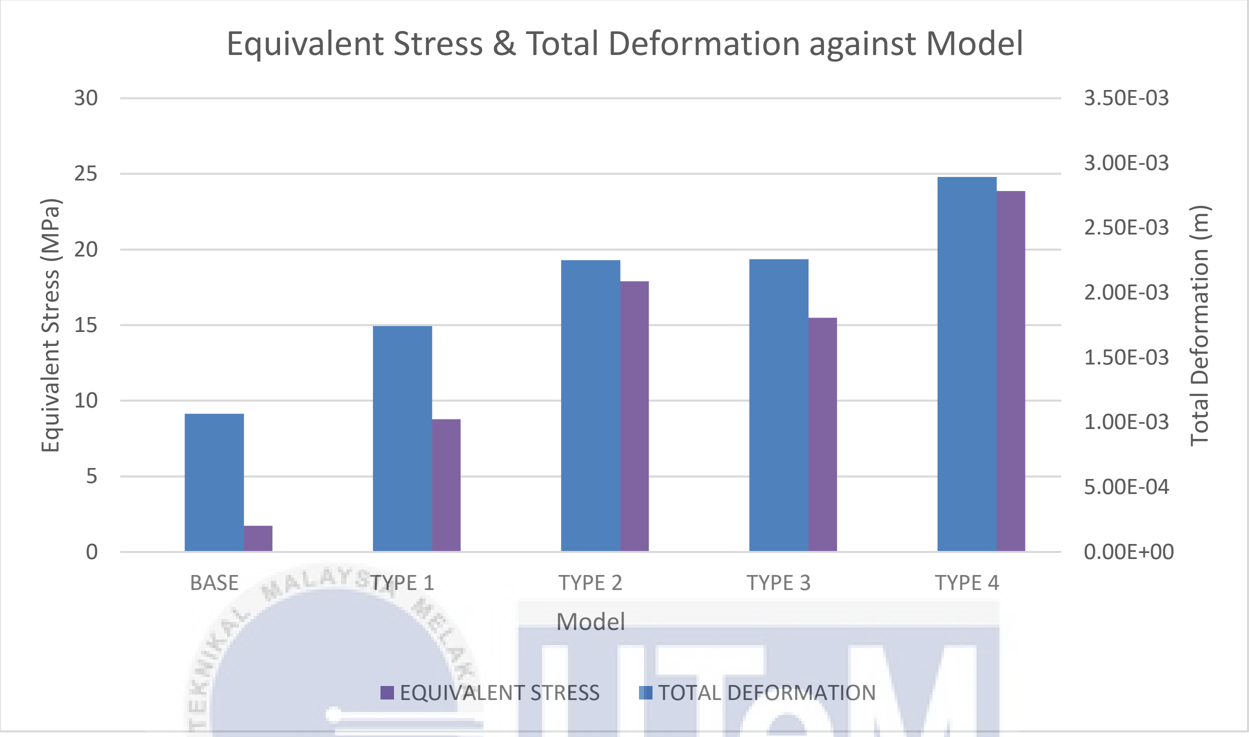


Figure 4.3.2 : Bar Graph Equivalent Stress & Total Deformation against Model

The equivalent stress is a key performance metric for disc brakes, indicating the overall stress experienced by the disc brake during operation. The Base model records the least stress (1.7351), while Type 4 records the most (23.868). This implies that Type 4, with its 15-degree curved groove and vent, might experience higher stress levels, possibly due to increased friction or heat generation.

Total deformation, on the other hand, indicates the extent to which the disc brake changes shape under stress. The Base model shows the least deformation (1.07E-03), while Type 4 shows the most (2.89E-03). This could be due to the design of the grooves and vents, which might affect the structural integrity of the disc brake. The 15-degree curved grooves and vents in Type 4 may cause more deformation, potentially due to the increased stress it experiences.

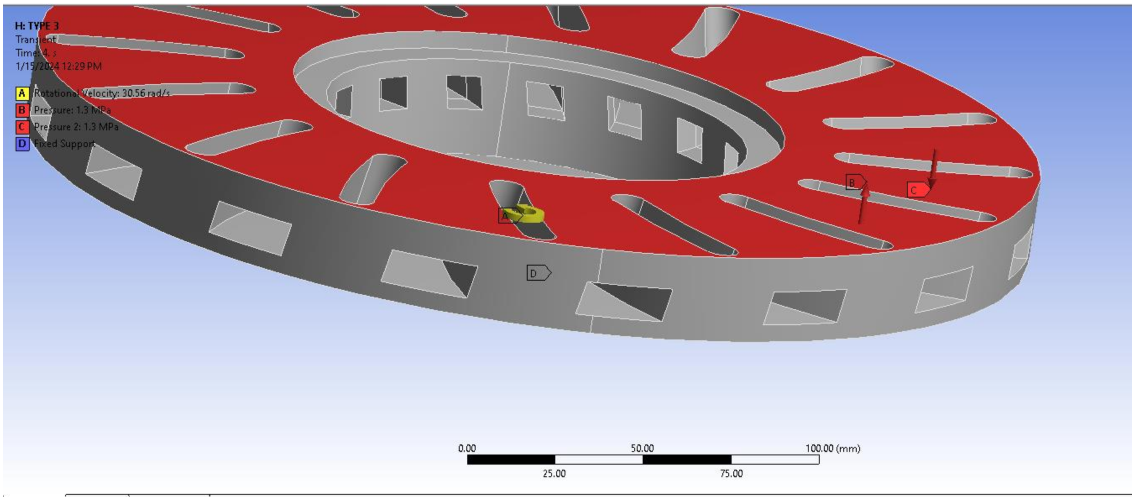


Figure 4.3.1 : Condition of Model 3 before simulation

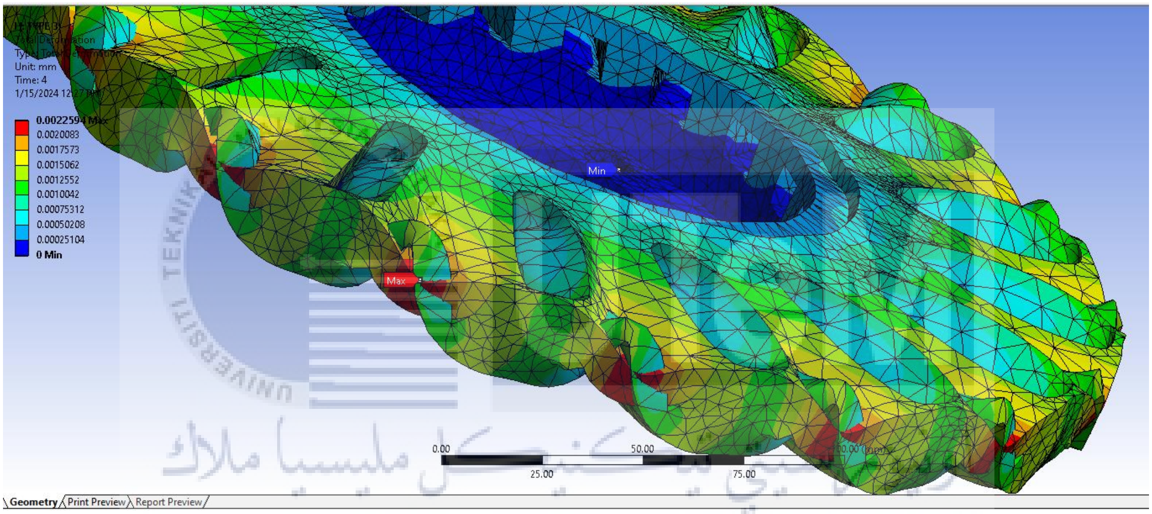


Figure 4.3.3 : Condition of Model 3 after simulation (Total Deformation)

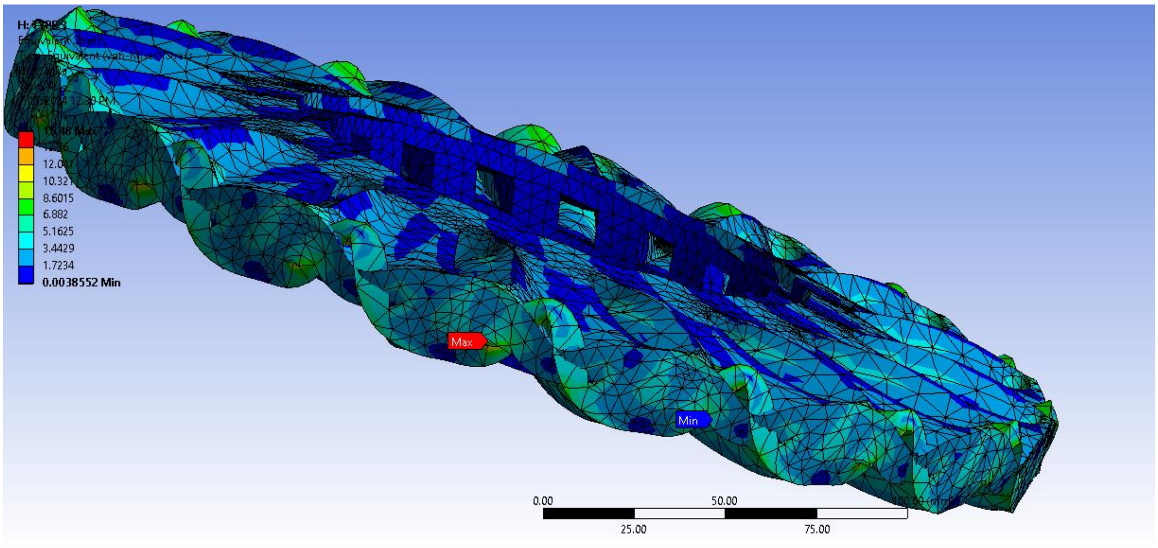


Figure 4.3.3 : Condition of Model 3 after simulation (Equivalent Stress)

The design of the grooves and vents in disc brakes plays a significant role in stress distribution and deformation. The grooves and vents increase the surface area of the disc brake, enhancing heat dissipation. Moreover, the design of the grooves and vents affects the airflow around the disc brake. Proper airflow is essential for carrying away the heat generated during braking. The grooves and vents facilitate airflow, helping to cool the disc brake more efficiently. The curved design of the grooves and vents in Types 2, 3, and 4 may allow for better airflow compared to the straight design in Type 1, potentially explaining their lower maximum temperatures. However based on observation and comparison between Figure 4.3.1 and Figure 4.3.2, the cause of reduction in structural stability was due to design of vent. Most deformation and stress focus at area of the vent. In matter of improving the design, disc brake need to remove the vent or change the geometry of the vent to improve the stability of the structure.

In conclusion, the design of the grooves and vents in disc brakes, which influences the surface area and airflow, is a critical factor in stress distribution and deformation. This underscores the importance of design considerations in enhancing the performance and longevity of disc brakes. The role of groove and vent design in stress distribution and deformation, as suggested by the data, could be a particular focus. The influence of these factors on disc brake longevity and brake noise is also noteworthy, as higher stress levels and deformation can lead to faster wear and tear, reducing the brake's lifespan and potentially increasing brake noise. Future research could delve into these aspects to further optimize disc brake design.

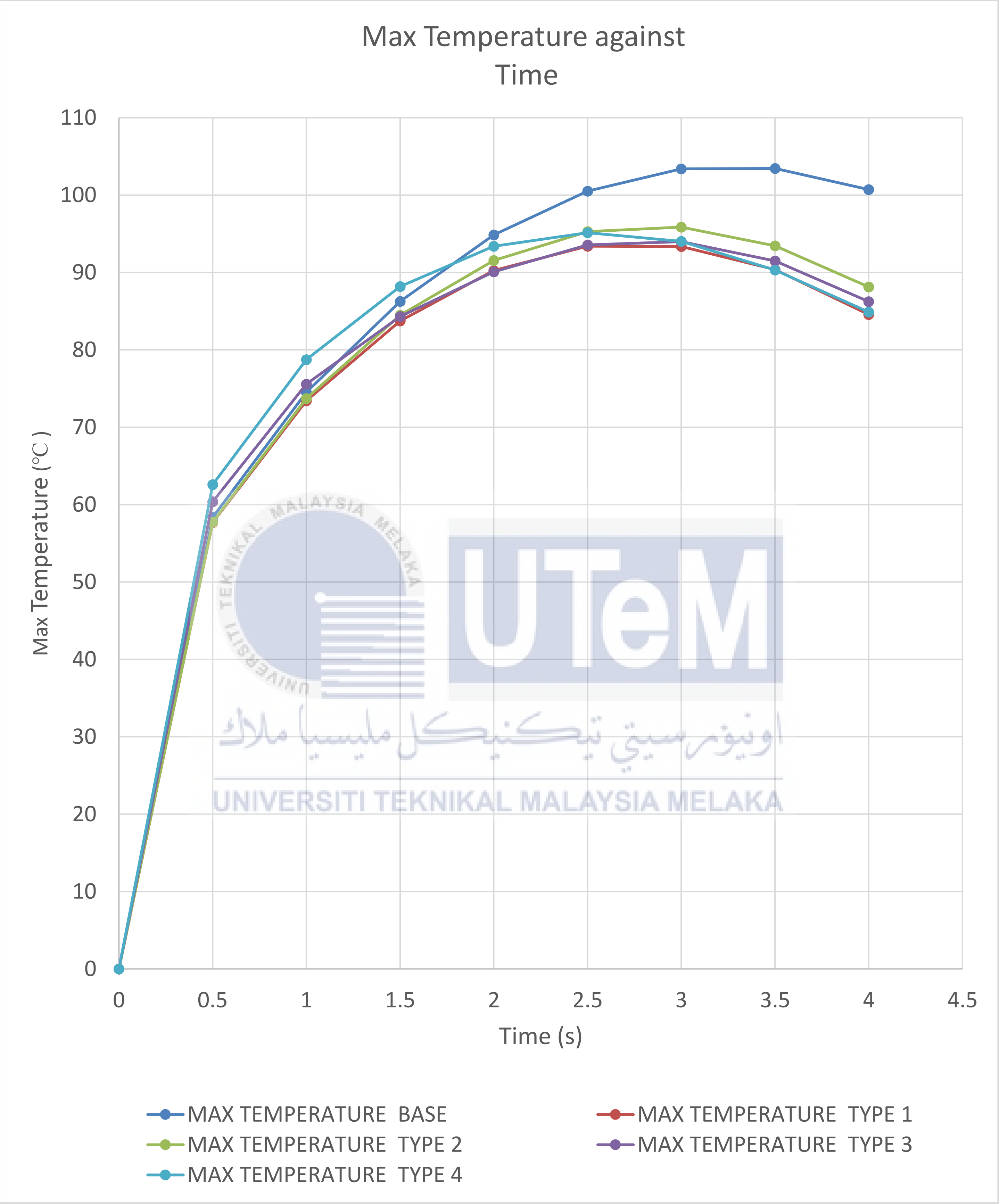


Figure 4.3.4 : Line Graph of Max Temperature against Time

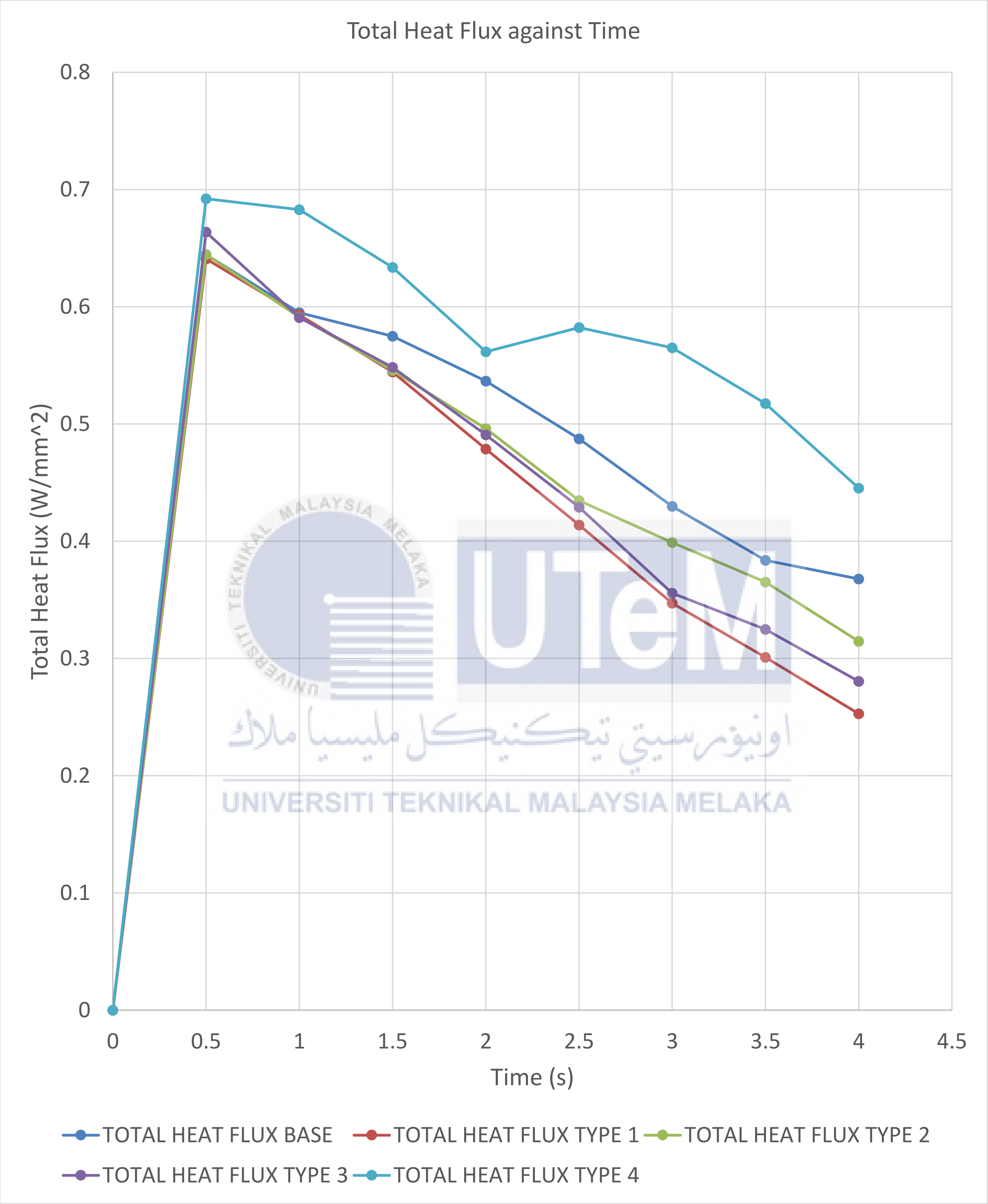


Figure 4.3.5 : Line Graph of Total Heat Flux against Time

By comparing the 4 developed design, the model with great heat distribution, great heat dissipation and good strength is Model Type 3. Model Type 3 has achieved 14.39% improvement in generated maximum temperature, 23.73% improvement in total heat flux. Although it has no improvement in structural aspect, the difference in equivalent stress not too high which is 13.7449 MPa , better than Model Type 4 with difference of 22.1329 MPa.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The heat distribution on a disc brake is primarily determined by temperature and heat flux. When the brake pads apply pressure on the disc, mechanical energy is converted into thermal energy due to friction. This heat flux is then computed in a transient thermal analysis to determine the temperature distribution in the disc. The heat is dissipated in the disc material, altering the temperature distribution. The temperature difference between the disc and the surrounding air facilitates heat dissipation. The temperature distribution is then used in a structural analysis to compute thermal stresses at various solution times. Therefore, temperature and heat flux are critical in determining the heat distribution on a disc brake, which in turn affects its performance and lifespan.

From the research it can be concluded that Model Base is the most stable design for disc brake rotor and among the 4 developed design, Model Type 3 is the disc brake rotor with the best in term of thermal and structural aspect. It can be conclude that Model Type 3 is the new design that improve thermal behavior of disc brake rotor.

5.2 Recommendations

For future improvements, the accuracy of the analysis and performance of disc brake rotor can be improved by:

i) Take the dimension from actual disc rotor. It because the actual dimension of disc brake rotor can give the result closer to real-world component. It will greatly impact the heat management, structural stability and design optimization of the disc brake rotor.

ii) Use actual input from actual car. It will give more precise input to be applied on the simulation which lead to more accurate analysis. The focus on vehicle also make the research more feasible as the result can be directly related to the specific car.

iii) Varies the angle of groove and vent. Improving the ventilation feature is one of the component to improve the performance of the disc brake in realm of heat management and structural stability.

iv) Varies the velocity during the analysis to know the range of effectiveness of ventilation features on the disc brake.

v) Make actual test to compare between simulation and experimental method. It s to validate the analysis whether it is use the correct method or not.

vi) Use the Computational Fluid Dynamic (CFD) analysis to get more precise input. As the analysis consider the airflow distribution around the brake rotor and the heat transfer coefficient on each surface of the disc brake.

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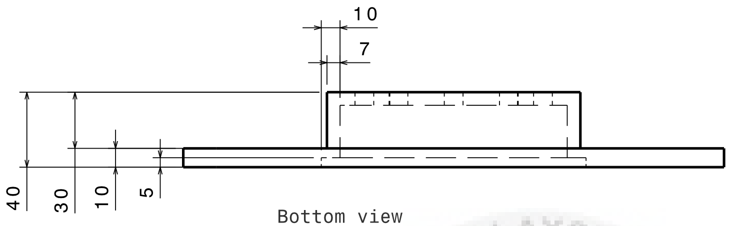
APPENDICES



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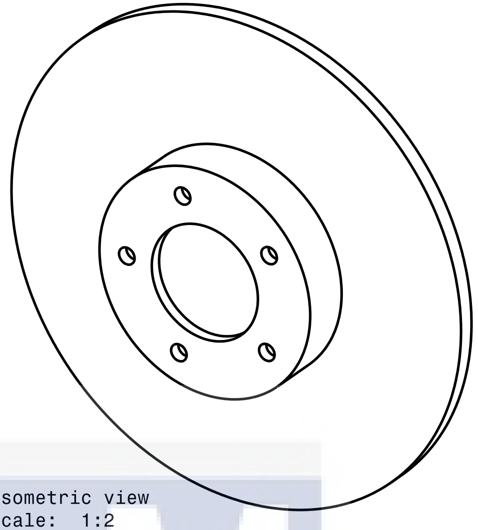

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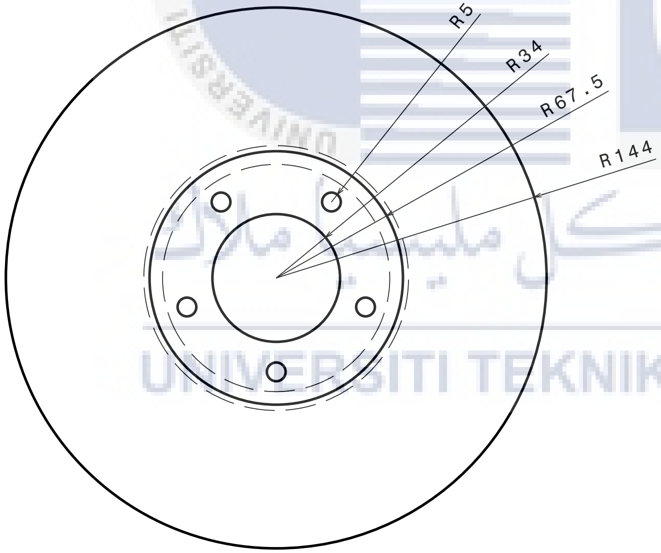


Front view
Scale: 1:2

Left view
Scale: 1:2

MUHAMMAD AMIR BIN AB HALIM
B092010075
For PSM Purpose

DISC BRAKE
SOLID

DRAWN BY
Amir Halim

DRAWING TITLE
MODEL BASE

CHECKED BY
Mr. Zulhusni

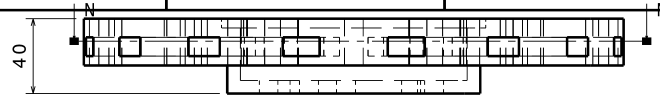
DESIGNED BY
Amir Halim

SIZE
A2

DRAWING NUMBER
Part1

SCALE 1:2

SHEET 1/1



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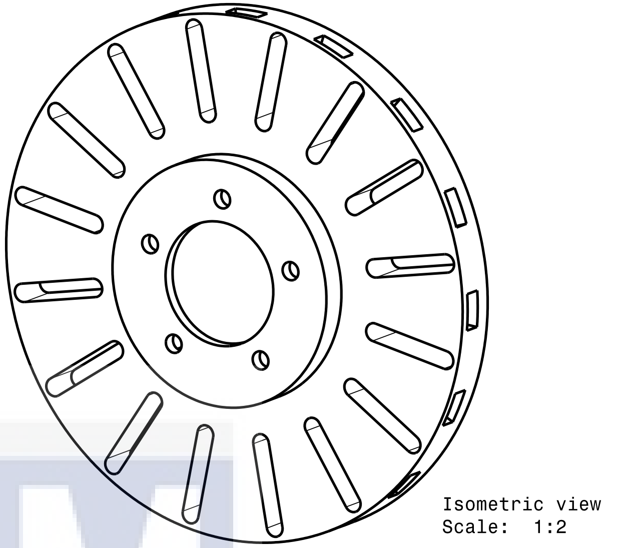

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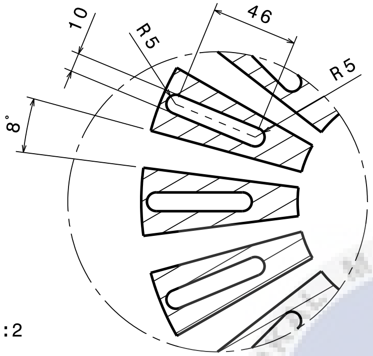

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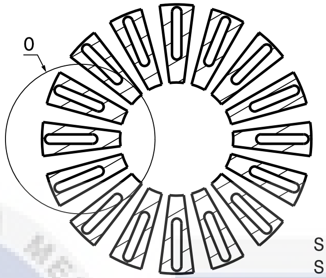
Scale: 1:2



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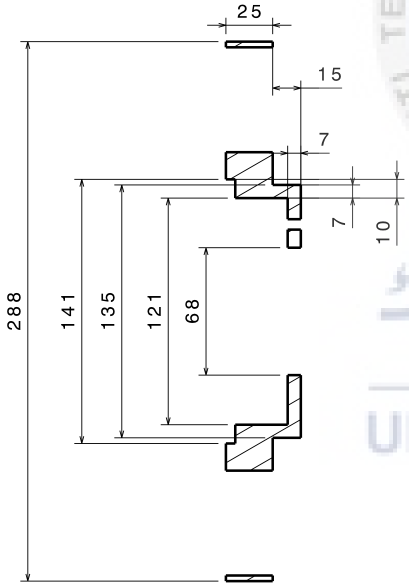

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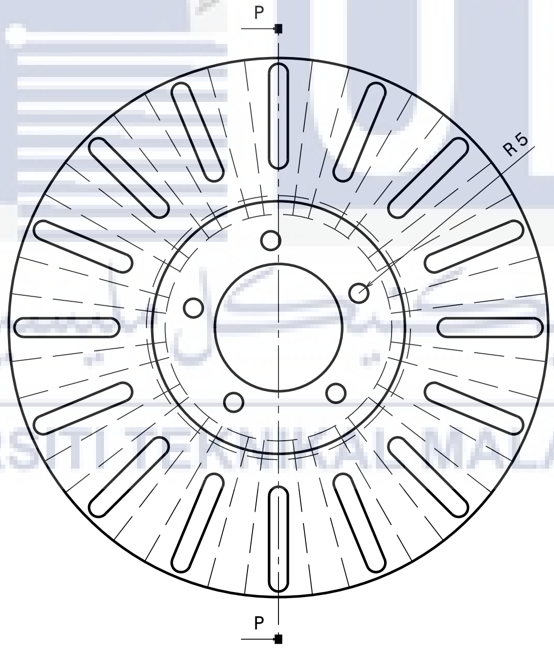

Front view
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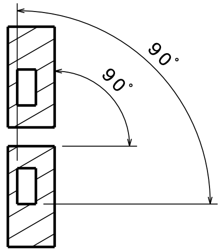
Right view
Scale: 1:2



Section cut M-M
Scale: 1:2

MUHAMMAD AMIR BIN AB HALIM
B092010075
For PSM Purpose

DISC BRAKE
STRAIGHT GROOVE + STRAIGHT VENT

DRAWN BY
Amir Halim

DRAWING TITLE
MODEL TYPE 1

CHECKED BY
Mr. Zulhusni

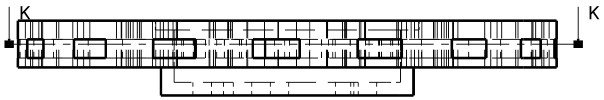
SIZE
A2

DRAWING NUMBER
Part1

DESIGNED BY
Amir Halim

SCALE 1:2

SHEET 1/1



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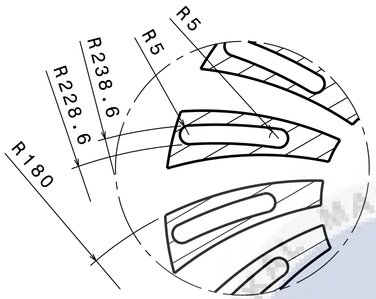

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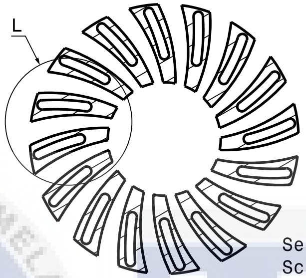

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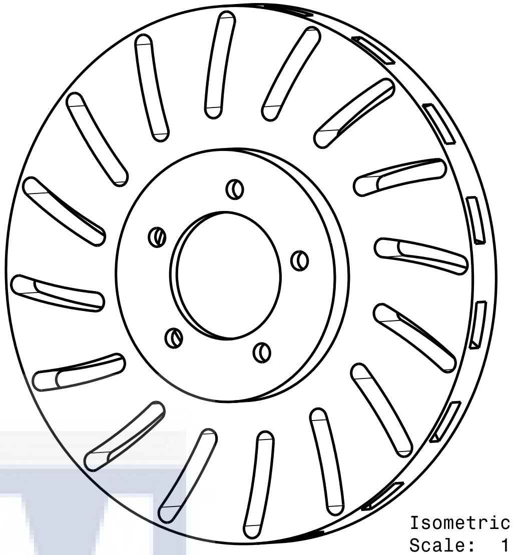

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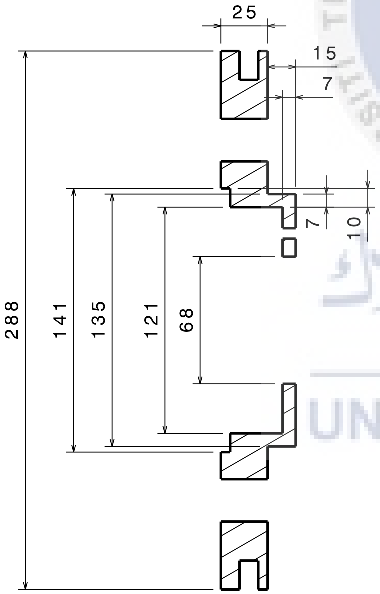

Section cut J-J
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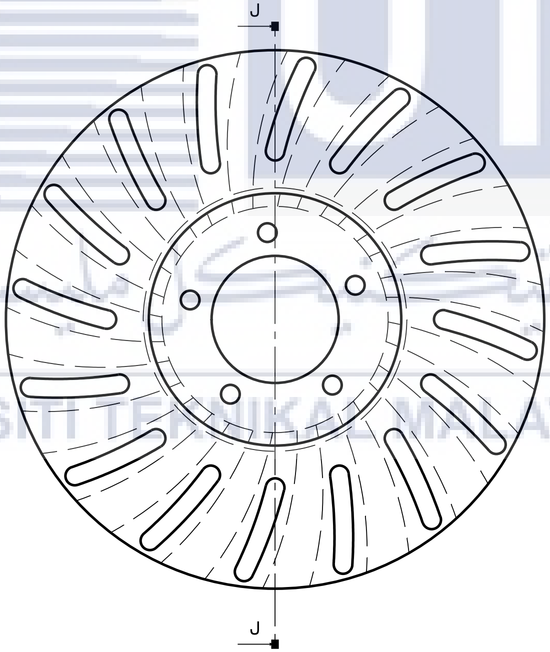

Front view
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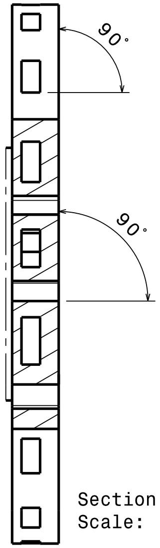
Right view
Scale: 1:2



Section view E-E
Scale: 1:2

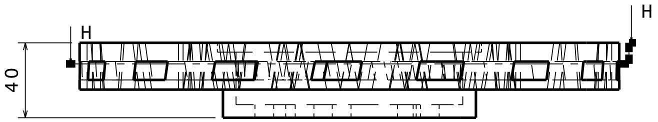
MUHAMMAD AMIR BIN AB HALIM
B092010075
For PSM Purpose

DISC BRAKE
CURVED GROOVE + CURVED VENT

DRAWING TITLE
MODEL TYPE 2

DRAWN BY
Amir Halim
CHECKED BY
Mr. Zulhusni
DESIGNED BY
Amir Halim

SIZE
A2
DRAWING NUMBER
Part1
SCALE 1:2
SHEET 1/1



Top view
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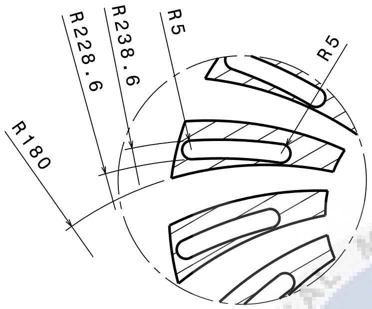

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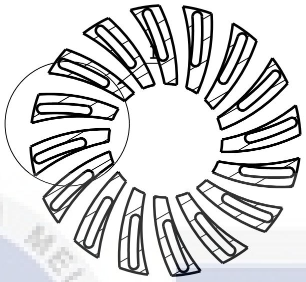

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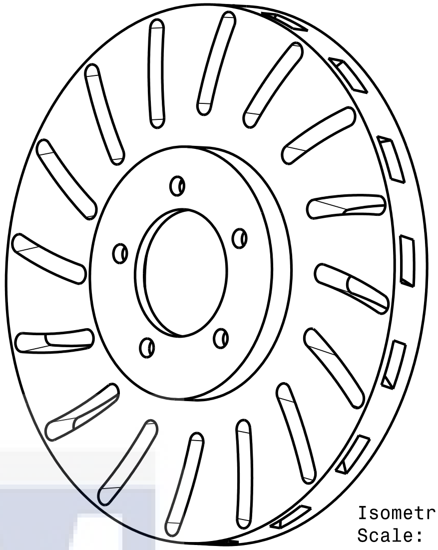

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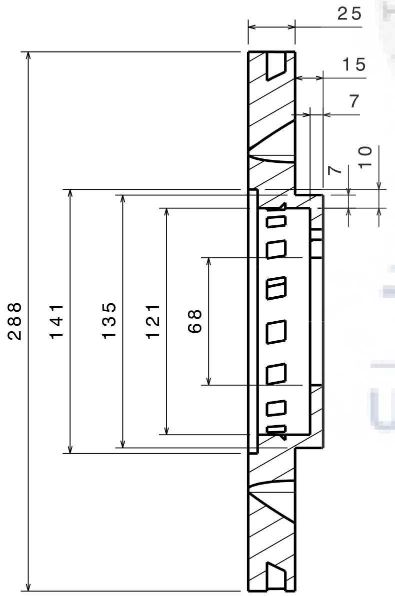

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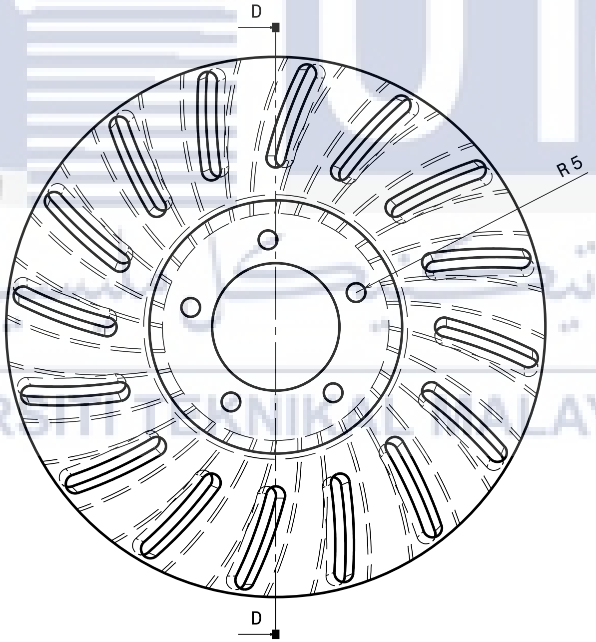

Front view
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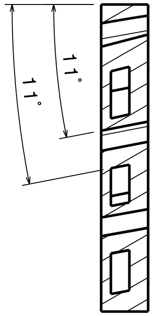
Right view
Scale: 1:2



Section view C-C
Scale: 1:2

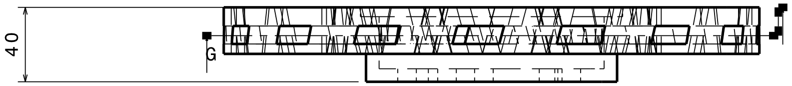
MUHAMMAD AMIR BIN AB HALIM
B092010075
For PSM Purpose

DISC BRAKE
11° CURVED GROOVE + 11° CURVED VENT

DRAWING TITLE
MODEL TYPE 3

DRAWN BY
Amir Halim
CHECKED BY
Mr. Zulhusni
DESIGNED BY
Amir Halim

SIZE A2
DRAWING NUMBER Part1
SCALE 1:2
SHEET 1/1



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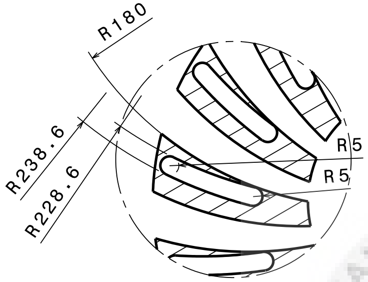

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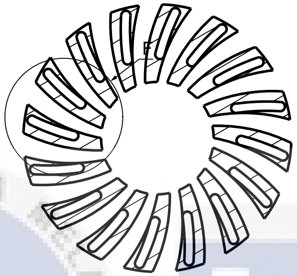

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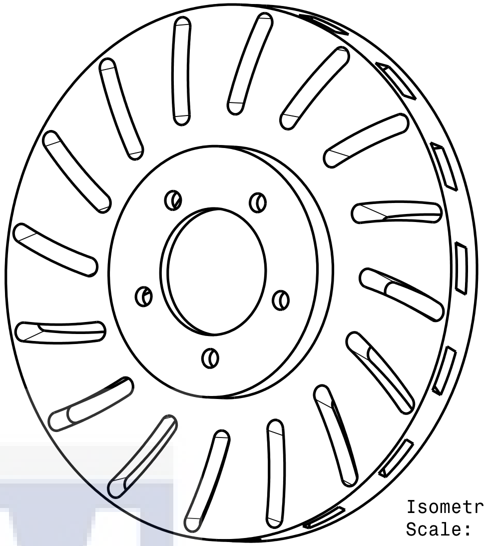

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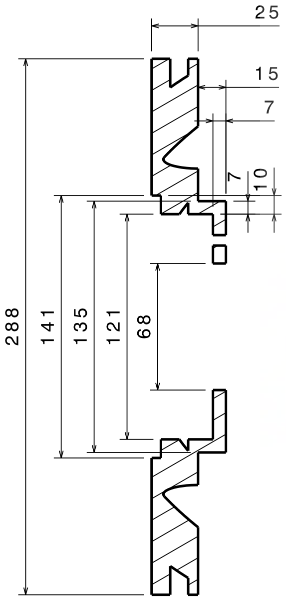

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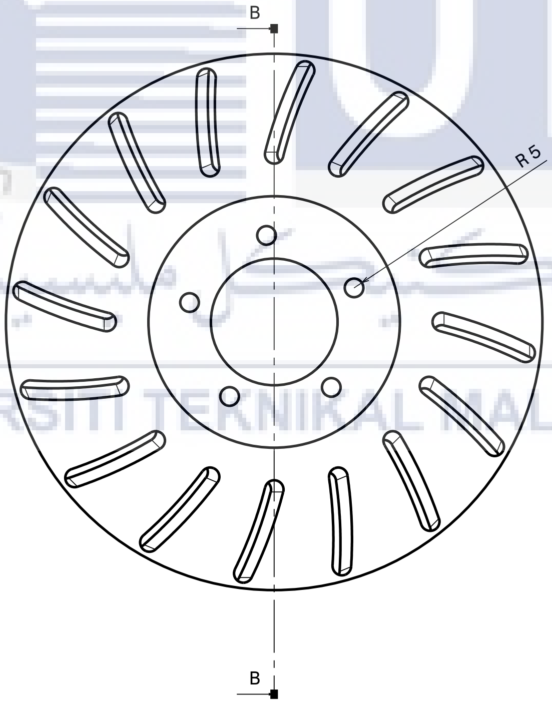

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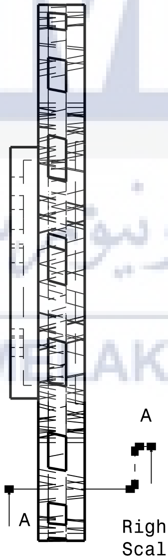

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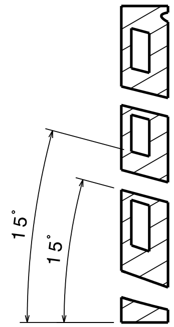

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MUHAMMAD AMIR BIN AB HALIM
B092010075
For PSM Purpose

DISC BRAKE
15° CURVED GROOVE + 15° CURVED VENT

DRAWING TITLE
MODEL TYPE 4

DRAWN BY
Amir Halim

CHECKED BY
Mr. Zulhusni

DESIGNED BY
Amir Halim

SIZE
A2

DRAWING NUMBER
Part1

SCALE 1:2

SHEET 1/1