THERMAL STRESS ANALYSIS ON FORMULA VARSITY (FV) DISC BRAKE ROTOR BY USING FINITE ELEMENT ANALYSIS (ANSYS)

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A report submitted

in fulfillment of the requirements for the degree of

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DECLARATION

I declare that this project entitled "Thermal Stress Analysis On Formula Varsity (FV) Disc Brake Rotor By Using Finite Element Analysis (ANSYS)" is the result of my own work except as cited as reference.

Signature : ……………………………

Name : Muhamad Khairul Nizam Bin Nasri

Date : ……………………………

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Plant & Maintenance).

Signature : ....

Name of Supervisor : Mohd Zaid Bin Akop

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

As we know, the braking system is important part in a vehicle. The braking system function is to slow down and slowly stop the vehicle. In this Final Year Project, the braking system was applied in Formula Varsity Car. The disc brake rotor of this Formula Varsity is design and creating by using SolidWork. This research project consists of thermal stress analysis on Formula Varsity Car disc brake rotor by using Finite Element Analysis (ANSYS). The analysis consists of steady-state and transient analysis to determine the temperature distribution on the disc brake rotor. Thermal analysis is also performed by calculating the heat transfer coefficient on the disc brake rotor based on the obtained results. The value of heat transfer coefficient has been used in steady-state and transient analysis. The findings of this research are to improve the brake performance in Formula Varsity Car and analyzed the stress distribution on the disc rotor during operation. This project also was conduct to see whether the design of disc brake rotor will overcome the failure or not. The results shows the temperature of disc brake rotor is increasing when the brake is applied and it slowly cool down when the brake pad is released. The material that has been used for this research can withstand the heat generated and high stress during the braking process.

ABSTRAK

Seperti yang kita tahu, sistem brek adalah bahagian yang penting di dalam sesebuah kenderaan. Sistem brek berfungsi untuk memperlahankan dan memberhentikan kenderaan. Di dalam projek sarjana muda ini, sistem brek telah digunakan ke atas kereta Formula Varsity. Reka bentuk cakera brek Formula Varsity direka dengan menggunakan SolidWork. Penyelidikan ini terdiri daripada analisis tegasan haba ke atas cakera brek Formula Varsity dengan menggunakan Finite Element Analysis (ANSYS). Analisis ini terdiri daripada keadaan mantap analisis dan fana analisis untuk menentukan pengedaran suhu di dalam cakera brek. Analisis tegasan haba juga dilakukan dengan mengira pekali pemindahan haba pada cakera brek berdasarkan maklumat yang telah dijumpai. Nilai pekali pemindahan haba telah digunakan di dalam keadaan mantap analisis dan fana analisis. Hasil kajian ini adalah untuk meningkatkan prestasi brek di dalam Formula Varsity dan menganalisis agihan tegasan pada pemutar cakera semasa ia beroperasi. Projek ini juga dijalankan untuk melihat sama ada reka bentuk cakera brek akan mengatasi kegagalan ataupun tidak. Keputusan menunjukkan suhu cakera brek rotor semakin meningkat apabila brek digunakan dan ia perlahan-lahan menjadi sejuk apabila brek pad dilepaskan. Bahan yang telah digunakan di dalam kajian ini boleh menahan haba yang dihasilkan dan tekanan yang tinggi semasa proses pembrekkan.

ACKNOWLEDGEMENT

First of all I would like to thanks Allah S.W.T because give me the opportunity to study at this level. For the final year student, we have to complete our own project that called Final Year Project. The title of the project has been provided and we have to choose the title that we want during the last semester of third year. I would like to thanks to my supervisor, En Mohd Zaid Bin Akop because has given his cooperation during my project. He also helps me to complete my final year project by gives useful information and inspiration from the start until the last of my research.

I would like to thanks to both of my parents and my family because give their best to support me to complete my project. I also want to thanks to all my friends because without them I cannot do this project on my own. When I have a problem, my friends will give moral support and help me if they are anything that they can help.

For the person that I have not mentioned their name, I also want to thanks them that involved either direct or indirect in my final year project. This project will be impossible for me to complete without the support from all them.

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LIST OF ABBEREVATIONS & SYMBOLS

FV	Formula Varsity
CGI	Composite Graphite Iron
FEA	Finite Element Analysis
Q	Rate of Heat Transfer
h	Convection Heat Transfer Coefficient
As	Surface Area of Rotor
T_s	Surface Temperature
T_∞	Ambient Temperature
ε	Emissivity
σ	Stefan Boltzmann's Constant
[K]	Heat Conduction Matrix
{u}	Vector of Unknown Temperature
[R]	Radiation Exchange Matrix
{P}	Vector of Constant Applied of Heat Flow
{N}	Vector of Temperature Dependent Heat Flow
K	Kelvin
$\{\dot{u}\}$	du/dt
MPa	Mega Pascal
°C	Degree Celsius

CHAPTER 1

INTRODUCTION

1.1 Background Research

Formula Varsity (FV) is an event that challenges engineering students that come from entire Malaysia to design, build and test their self-developed formula style racing cars. In this event also the technical skills of students were tested. It covers every aspects of automotive industry including design, assembly and prototype building and testing of the product. The most important part of this Formula Varsity is brake system. Brakes are required to stop the vehicle within the possible distance. It also functions to slow down the car when approach a corner or to stop the car. The kinetic energy of vehicle was converting into heat energy by friction which is dissipated into atmosphere. A disc brake assembly consists of disc rotor, calipers and disc pad. Disc brake is widely used because its design is far superior to that of drum brakes. Disc brakes use a slim disc and small caliper to halt wheel movement. Fluid is used to transfer the movement of the brake pedal into the movement of the brake pads. Friction between the contact area of pad and disc during braking process cause wear as the pad degraded gradually.

Unevenness of the pressure distribution causes uneven wear and consequently shortens the life of disc rotor. The dynamic contact pressure distribution in a disc brake system remains impossible to measure through experimental methods. This makes numerical analysis using the finite element method an indispensable alternative tool to its prediction. Simulation analysis is used to predict the failure of the brake disc rotor and help design improvement on the production of disc rotor. This project present the stress analysis of disc brake by analyzes in computer aided engineering (CAE) software. CAE or more specifically finite element analysis (ANSYS) will analyzed the stress distribution on the disc rotor during operation and prediction of failure regions can be made.

1.2 Problem Statement

As we know the speed of Formula Varsity car is a quite fast. The main problem is the higher the speed of the car, the lower their tendency to stop that car. Due to the higher speed, the braking system that has been used on the FV car must be good enough to slow and stop the car. The brake disc rotor on the car must be able to working at high temperature and high pressure. That is because when brake pedal is pressed, the brake disc rotor will heat up and slowing down the car. The braking efficiency is reduced when the brake pad starts to get too hot. This malfunction of the brake system is called brake fade. Other than brake fade, disc rotor also undergo cracking, coning, thermal judder and others possible effects due to friction. The usage of the brake may promote wear to disc and brake pad.

Uniform disc and pad wear, brake temperature, and more even friction coefficient could only be achieved when pressure distributions between the pads and disc are uniform. In addition, unevenness of the pressure distribution causes uneven stress distribution that can lead to uneven wear and consequently shortens the life of disc and pad. The design of brake disc rotor is important to determine their efficiency to stop the car. This project will focus on the simulation analysis of brake disc rotor on the Formula Varsity car. The stress distribution of disc from simulation result can be analyzed by using Thermal Stress Analysis (ANSYS). Is that the design will effects the brake system? It will be proving when this project is finish.

1.3 Objective of the Study

The purpose of this project focuses on thermal stress analysis on the brake disc rotor. The result of this project will cover based on the objective. The objectives are as follow:

a) To investigate the temperature distribution of Formula Varsity disc brake rotor.

b) To analyze the thermal stress analysis on Formula Varsity design of disc brake rotor.

1.4 Scope of the Work

The scope of this project is covered;

- Literature review about brake disc rotor component, working principles and theories that have been used.
- Design of 2D and 3D model of brake disc rotor by using Solid Works (2016).
- FE model of brake disc rotor (Meshing of geometry model).
- Analyze the thermal distribution of the brake disc rotor by using finite element analysis (ANSYS).
- The discussion of brake disc rotor due to ANSYS result.
- Final justification of thermal stress analysis on the Formula Varsity brake disc rotor.

CHAPTER II

LITERATURE REVIEW

2.1 Overview

This chapter is about the introduction of brake disc rotor and their working principles. There are many type of brake disc rotor that has been listed but the chosen one is ventilated disc rotor. That is because there are many advantages than disadvantages that have been found while this research is going on. In this chapter also explanation about the heat transfer such as conduction, convection and radiation that effect the brake disc rotor. The discussion concepts the heat transfer are explained including of thermal transient and modeling consideration. It can be concluded that heat transfer from high temperature to lower temperature. That means the heat from the disc rotor transfer into brake pads and dissipated into air due to the design of disc rotor with ventilated type. Finite element analysis (ANSYS) was detailed discuss about the finite element analysis stage and modeling. The history of disc brake development will be discussed in the next section.

2.2 Introduction of Braking System

One of the most important parts of vehicle is Braking System. Braking System is the system where the speed of vehicle is reduces by using brake as a mechanical device. As we know the braking system able to slow and stop the vehicle by apply the pressure at the brake pad. Actually the brake pedal is connected by brake booster. The brake booster multiplies and transfer the force produced by stepping on the brake pedal to the master cylinder. In turn, the master cylinder uses that amplified force to pressure the brake fluid from its reservoir through hydraulic lines toward the two fronts and rear brakes. The vehicle will be slow down due to the pressure that has been applied at the brake rotor. The harder the pedal was pushed, the more pressure is applied to the brakes.

The friction brakes on vehicle store braking heat in drum brake or disc brake while braking and then carry out it to the air slowly. Some of vehicle use their engine to brake when the vehicles travelling downhill. In this case the brake pedal of vehicle with hydraulic brakes was pushed against the master cylinder, in basically a piston pushes the brake pad against the brake disc which slows down the wheel down. The same system was used on drum brake as the cylinder pushes the brake shoes against the drum which also slows down the wheels of vehicle. Almost all wheeled vehicle have a brake or some sort of that. For example shopping carts and baggage carts have their own brake systems to use in moving ramp. Some aircraft also designed with air brakes to reduce their speed in flight.

In this research, the braking system was focused on the mechanical brakes. That is because, mechanical brake is more suitable brake used in Formula Varsity. Actually, the type of brake is choose depend on their design of vehicle due to performance, weight, and etc.

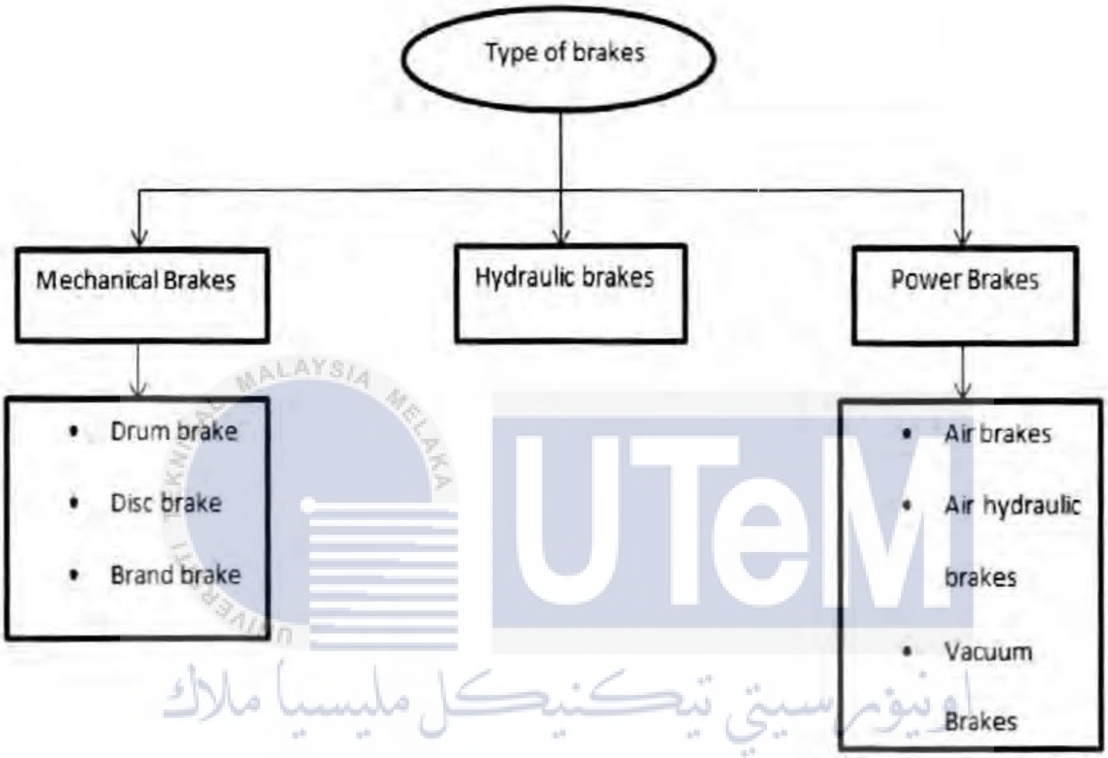


Figure 2.1: Type of brakes

Illustration above show the types of braking system used by vehicle .There are many types of brakes that have been used now days such as mechanical brakes, hydraulic brakes and power brakes. The braking system is the most critical system in vehicle. The maintenance and proper functioning are important to avoid from any undesirable things happens when driving.

2.3 History of Braking System

The first braking system was designed before the Roman Empire was build. The material of braking system back days is only using wooden block and lever. By pulling the lever, the wooden block will forced against the wheels and due to the frictional force the vehicle will slow down. The systems that have been used like hand break nowadays. After 2000 years went through time, there is no improvement for this technology. This technology also was applied in early locomotive as their braking system. This below picture show the early designed of braking system.

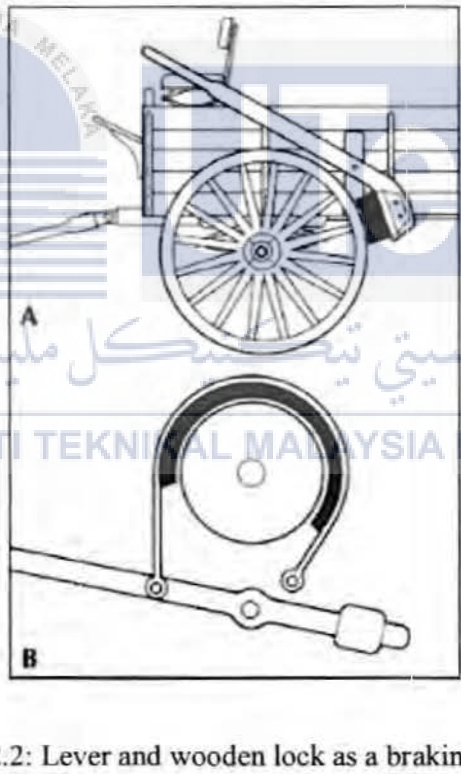


Figure 2.2: Lever and wooden lock as a braking system

(Source: http://kids.britannica.com/students/assembly/view/53011)

In the 20th century, the improvements of braking system start to take revolutions. There are many advances braking system was designed in automotive and trucking industries. Early automobile had band brake and then followed by drum brakes. While in 1920's to 1940's, hydraulic system was a major improvement in back days by allowing more consistent force distribution. Disc brake often used on cars and trucks since 1960's due to the improvement of fade resistance, the shorter time take to stop the vehicle. The disc brakes have their own disadvantages like drum brake. Every time the forced is applied, the mass increase in temperature. For this case when the driver dealing with heavily loaded vehicles, this will be dangerous problem due to the brakes get overheat and performances of brake will reduce. Now a day, "retarders" was used to improve braking system due to overheat disc brake. "Retarders" mean the inability of air-cooled friction brakes to absorb energy for lengthen durations. This product has several types, which are auxiliary devices that provide "retarding" force. By reduce the usage on long downgrades and eventually lowers operating temperature, the life of the original brake is improved. The Illustration below shows the common types of retarders.

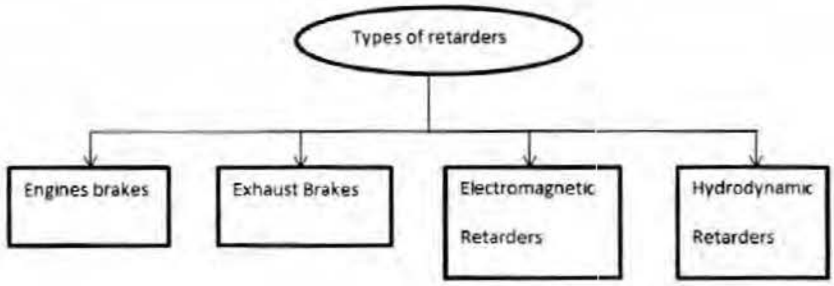


Illustration 2.3: Recent types of retarders used now days

2.4 Disc Brake

2.4.1 Introduction

In 1902, Frederick William Lanchester is the first person who invented disc brakes. The design had two discs in order to press against each other that cause friction and slow down the vehicle. As we know, the disc brake is better at slow down and stopping a vehicle than drum brakes. Mostly, disc brake was designed at the front of vehicle because their advantages to stop the car is high than drum brakes. For the sportier vehicles, they often used at the front and rear wheels. Disc brake main component contain of rotor, calipers assemblies and disc. For standard disc brake, they have one or two cylinders in the braking system and its also knows as one or two pot calipers. The higher the force needed, the higher the number of cylinder that has been used. The floating rotor was designed to solve the problem due to high vibration on disc brake.

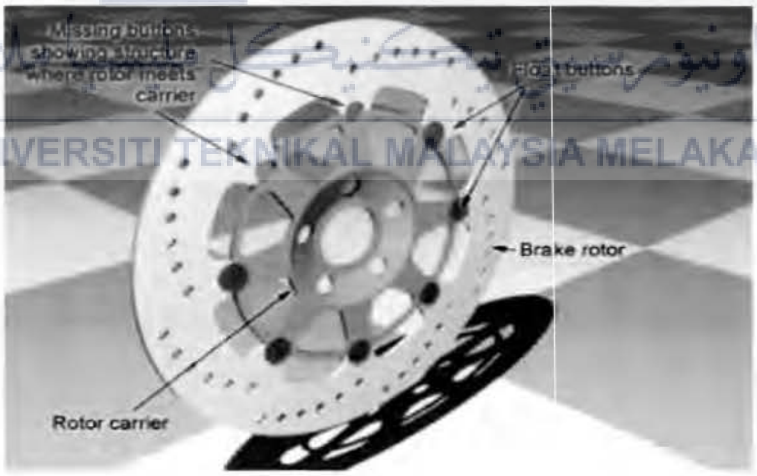


Figure 2.4: The floating rotor in system braking

(source: www.pakwheels.com(2016))

The wheels or drive plate was directly bolts with single piece of standard brake rotor. The driver will feels vibration if the mounting surface of driver plate is not perfectly flat. The floating rotor was designed in two pieces that is carrier and rotor. There other method of a floating brake rotor without a carrier by built the bolts that have their own floats buttons.

2.4.2 How Disc Brake Function

The brake systems work based on Pascal's Law. Two cylinders with piston connected to each other and fluid filled with incompressible fluid. When force is applied to the left piston, the fluid will transmit the force to the right piston surface. The left piston act as pedal side and the right piston act as the brake at wheel side. That mean, the energy transfer from pedal to the brake.

The wheel hub assembly holds the wheel and disc rotor. The bearing inside it allows their smooth rotation. The disc rotor is the part to which the brake pad squeezes against. This will create friction that retards the rotation of the wheel. The disc rotor produce a lot heat due to this friction and the drilled holes provides ventilation to remove this heat. The brake calipers assembly uses the hydraulic force from the brake pedal to squeeze the brake pads to the rotor surfaces. Thus creating friction and decelerate the wheel of the vehicle.

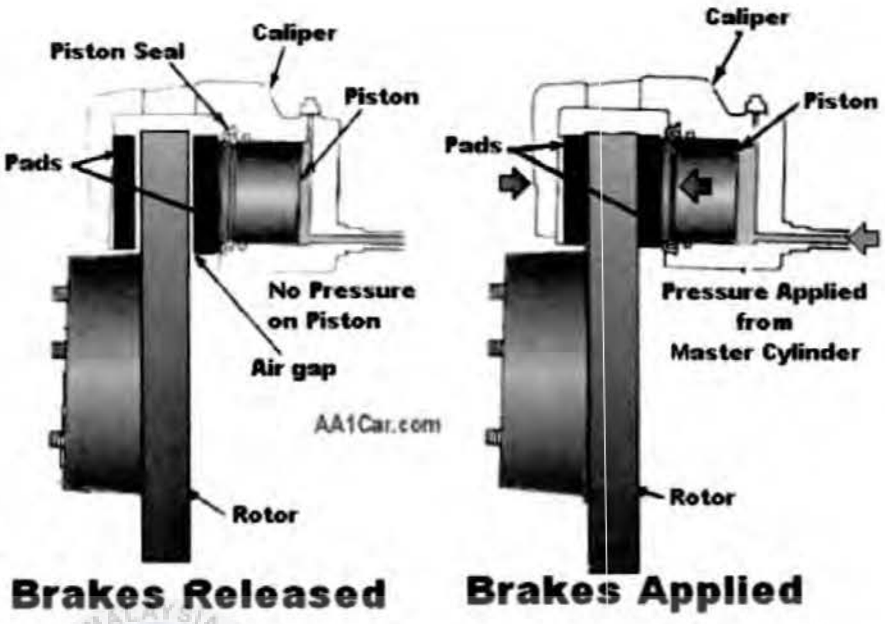


Figure 2.5: When the brake is released and applied by driver

(Source: http://www.aa1car.com/library/brake_calipers.htm)

Figure show how the disc brake works when the driver pushes the pedal brake. When the brake is forced, the caliper will receive the high pressure hydraulic fluid from the brake master cylinder. The fluid will push the piston which makes the inner brake pad to squeeze against the disc rotor surface. As a result, the fluid's backward force will push the caliper frame along the slide pin which makes the outer brake pad to squeeze against the other side of the disc rotor.

2.4.3 Disc Brake Components

There are component in disc brake that is important in designing of brake. The component include of brake pad, calipers assembly, rotor and hub assembly. The brake pad is squeezes to the spinning rotor to decelerate the speed of vehicle. In calipers assembly there are hydraulic and friction components that mounted outside diameter of the rotor. The rotor is equipped the frictional surface for the stopping the wheel. While, in the wheel hub assembly function as to holds the wheel and disc rotor.

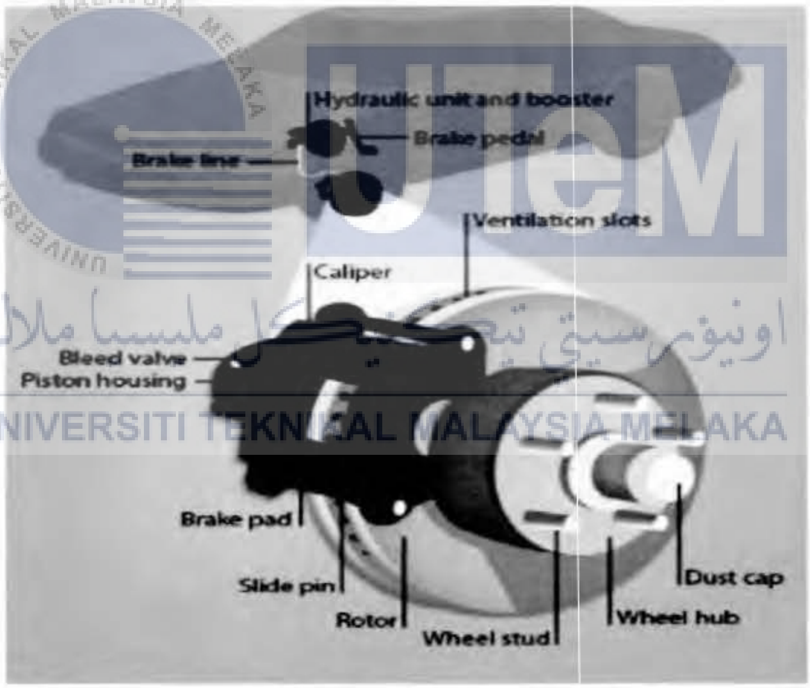


Figure 2.6: The components of disc brakes

(Source: http://www.tiresnorthfortmyers.com/brakes)

2.4.3.1 Brake Pads

Brake pads were used as friction linings in the disc brake system. The material of friction linings was depending on the application of the vehicle. On the others applications, the different of material were used at the inner and the outer pads. The material that has been used in this brake may be containing of ceramic, low metallic, semi metallic and etc.

Figure 2.7: Brake pads used as friction linings

(Source: https://www.aliexpress.com/w/wholesale-brake-pads.html)

The friction material mostly molded to the backing plate or rivets for holds together. A few internal noise dampening shims was used at the back of the pad to control the noise. Other ways to control the noise is by using slots and chamfers on the pad. When the thickness of brake pads reaches minimum specification or wear out, it should be replaced with the new one. Usually, the front pads wear is 2 or 3 time faster than the rear pads.

Now a days, with electronic brake proportioning, the rear brakes working heavily than front brakes and it will result differently. The rear pads wear maybe will same or faster than front pads wear.

2.4.3.2 Calipers

The function of calipers is to squeeze the pads against the rotors. The calipers are attached to a bracket of the steering knuckle and mounted over the rotors. Usually, the calipers have one or two pistons and some of calipers have more than 4 piston. The materials of calipers can be cast iron, steel or molded phenolic pistons.

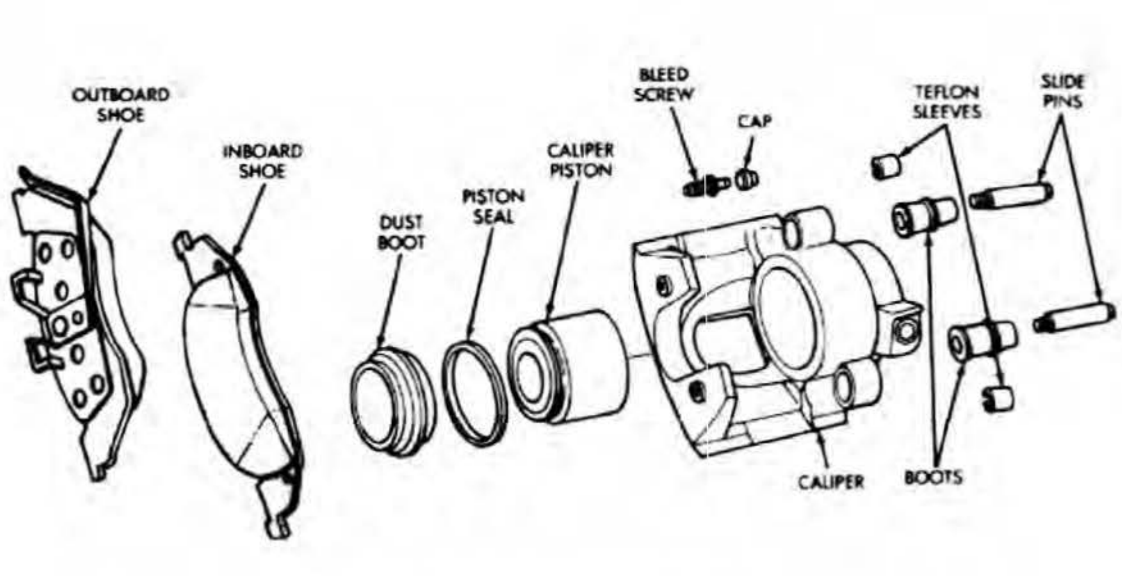


Figure 2.8: Disc Brake Caliper Diagram

(Source: http://www.autozone.com/repairinfo/repairguide/repairGuideContent)

Most calipers were designed "floating" on the inside of the caliper with the piston. It also has bushing or slides that enable the caliper to move sideways. For this case, when the brakes are applied, the calipers will center itself over the rotor. The slides inward and pulls the outside pad against the outside of the rotor when the piston is moves out pushes inside pad against the inside of rotor. The vehicle will slow down and stop when this clamping action occur. There are also calipers that have been designed do not slide that calls "fixed" calipers. There is no movement in or outward when the brake was applied. For the vehicles that have four wheels disc brakes, the rear calipers was design to have an internal parking brake mechanism to support the pads against the rotor. By pulling the parking brake cable, the calipers piston is pushes outward to lock the rear brakes. In some others applications, inside the rear rotor, there are "mini drum" that have been used for a parking brake

2.4.3.3 Rotor

There are two types of rotor that commonly used that is solid (unvented) and ventilated. In order to optimize airflow, the cooling fins between rotor faces are differently align. The design of rotor cooling vanes also can be design differently to optimize cooling by change the pattern or number of cooling fins. Most of rotor made up from cast iron, while the others made up of composite. The composite rotors are lighter than cast rotor because they flex more than solid that will affect the sensitivity due to vibration and run out.

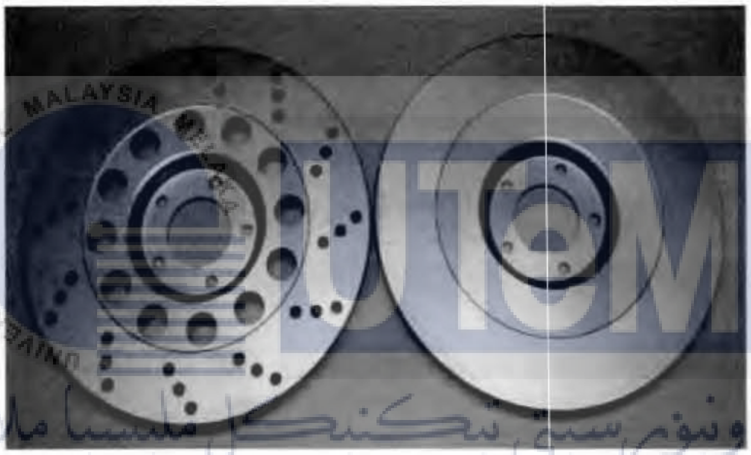


Figure 2.9: Vented (left side) and unvented rotor (right side)

(Source: F.H. Eaton & Associates (2016))

The speed of vehicle is decelerate when the calipers and pads of the brake was pressed against the both side of the rotor. This occur when the brake is apply and then causing the friction to slow down and stop the vehicle. In this research, vented disc was chosen as testing rotor due to their characteristic.

2.4.4 Advantages and Disadvantages of Disc Brake

They are good reason why manufactured started to moving away from the drum brakes more towards disc brakes. This is because the drum brakes have designed in enclosed style where the brake shoes are actually inside the housing. When friction occurs during braking, the heat will build up quickly. This will lead to brakes fade and adversely affect the performance of brakes. On disc brake style, it has an open air design with the rotor spinning. A lot of heat will dissipate into the open air and it will reduce the occurrence of brakes fade while braking. This exposure also works to constantly cool the rotor while rotating of wheels. Also on drum brakes, there will sometime get mud or water inside them that can affect wet. For the disc brakes, sometimes the centrifugal force of the brake rotor will actually spin the water off and that can improve braking in wet weather. The calipers and rotors can become a cosmetic things, it can be an appearance enhancement due to customer styles.

The disadvantages of disc brake are much more prone to noise when brake is applied. The noise will become continues grinding which often indicated as the lining have worn to the metal surface of the pads. In order to create the constant squeal when the pad have worn to their minimum thickness, the disc brake pad have the audible wear indicators which are small steel pins or clips that rub on the rotor. Many design of vehicle used disc brakes on the front wheels while drum brakes on the rear wheels. That is because disc brakes are more costly than the drum brakes. More skills required to operate disc brake compare to drum brake.

2.5 Brake Disc Rotor

2.5.1 Introduction

Brakes rotor is one of the important part or components in the braking system to slow down vehicle. In order to stop the wheels from spinning, the brake pads clamp down the brakes rotors. Brake rotors also have several different type like the others parts. The variety of brake rotors was designed to improve the efficiency of braking system. The example of brake rotors are drilled, slotted, solid and vented.

Figure 2.10: Show the type of brake disc rotors that have been used on vehicle

(Source: www.dcperformance.co.uk)

2.5.2 Ventilated Brake Rotor

Vented or ventilated brake disc rotor is commonly used on the front brake for vehicles. The two discs were put together by banks in between the base. There are air gap between them to help evacuate heat while braking. The purpose of the vented and internal cooling veins is to allow better cooling. Sometime, this rotor was designed with curved veins that function as small pump to pump the air out. This will affect the longer lasting of rotor that not easy to fade when working in high temperature.

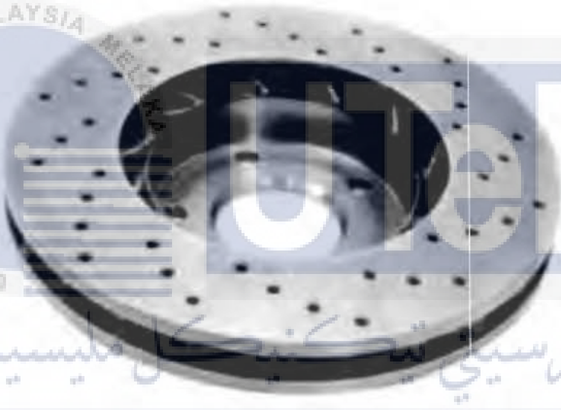


Figure 2.11: Ventilated disc rotor

(Source: http://www.frsport.com)

Ventilated brake disc rotor usually combined with others type such as drilled, two pieces rotor, slotted and ceramic rotor. This type of ventilated was design to improve the braking system in future based on condition needed.

2.6 Heat Transfer

2.6.1 Introduction

In this research, heat transfer is important to predict the energy transfer in brake disc rotor. The total mass of Formula Varsity will affect the temperature inside the brake disc rotor. When braking, the disc brake will transform from kinetic energy into thermal energy. This will result of overheating in brake disc rotors. If the disc overheats, the brake pads will stop working or melt. The braking power starts to fades due to this case.

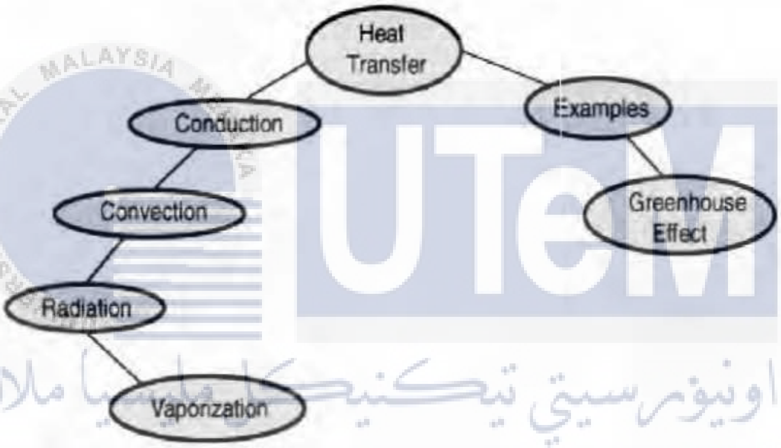


Figure 2.12: Heat transfer characteristic

(Source: hyperphysics.phy-astr.gsu.edu)

Normally, the heat transfer from a high temperature object to a lower temperature object. According to the First Law of Thermodynamic, heat transfer changes the internal energy of both objects.

2.6.2 Conduction

Conduction is a heat transfer via direct molecular collision. Thermal energy will transfer from an area with greater kinetic energy to a lower kinetic energy. The particle will collide with each other when the temperature increases. The most common form of heat transfer is conduction that occurs via physical contact. For example in the disc brake system, the brake pads and rotor will produce conduction of heat transfer due to physical contact.

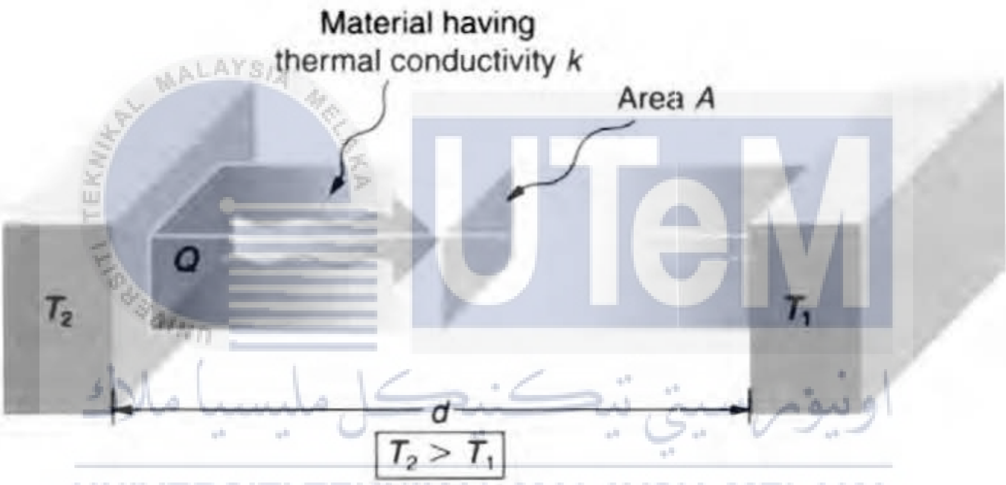


Figure 2.13: Heat transfer from high temperature into low temperature

(Source: https://www.khanacademy.org/science/physics/thermodynamics/specific-heat-and-heat-transfer/v/thermal-conduction)

To express the overall effect of conduction, the general form of temperature gradient term is written as a differential:

$$\frac{Q}{t} = kA\,(T_1 - T_2)/d \tag{2.1}$$

Where;

Q = Heat transferred in time

k = Thermal conductivity of the barrier

A = Area of contact

T_1 = High temperature

T_2 = Low temperature

d = Thickness of barrier

This equation was used to calculate the rate of conduction heat transfer. For heat transfer from disc rotor to brake pads can be calculated by applied that equation. The brake pads will receive the high temperature due to the heat transfer from disc rotor to brake pads. Conduction is also the strategy that has been used in design to move the heat from the disc pad interface to the vanes of rotor.

2.6.3 Convection

Convection is unlike a conduction occurs in liquids and gases. The transfer of heat through the movements of particles warm rise, cool particles fill in the space below. In this research, the convection is occurs when fluid flow in a thermal model of a brake system is make a contact with disc rotor. The pressure of forced air will move the air flow through the ventilated rotors and it will results of centrifugal acceleration. The heat that generated by the braking system will transferred to the moving air stream.

There is an equation for this convection by applied Newton's Law of cooling

$$Q = hA_s(T_s - T_\infty) \tag{2.2}$$

Where;

h = Heat transfer coefficient (W/m^2k).

A_s = Surface area (m^2)

T_s = Surface temperature (K)

T_∞ = Ambient temperature (K)

2.6.4 Radiation

The transfer of energy as waves and it travels through matter or empty space. This thermal radiation was called as infrared radiation due to magnetic radiation. The radiation does not rely upon any contact between sources of the heat. Radiation of heat from the rotor will have greater effect at high temperature. The beading of the tires will occur if this radiation not be controlled. The heat also can be transferred via thermal radiation which is considered as the boundary condition in different equation of heat conduction. The thermal radiation can be expressed and written as

$$Q = \varepsilon_1 A_1 \sigma\left({T_1}^2 - {T_2}^2\right) \tag{2.3}$$

Where;

ε_1 = Emissivity

A_1 = Enclosed surface

σ = Stefan Boltzman ($5.669 \times 10^{-8}/m^2K^2$)

2.6.5 Steady-State Analysis

In this steady state analysis, the temperature distribution of disc rotor under steady state was determined. The heat storage effect change over the period of time was ignored. The general form of equation for steady-state heat transfer can be express as;

$$[K]\{u\} + [R]\{u + T_{abs}\}^{2} = \{P\} + \{N\} \tag{2.4}$$

Where;

K = Heat conduction matrix

u = Vector of unknown temperature

R = Radiation exchange

T_{abs} = Temperature offset from the absolute required for radiation calculation

{P} = Vector of constant applied of heat flow

{N} = Vector of temperature dependent heat flow

2.6.6 Transient Analysis

Transient analysis was used to determine the temperature distribution of disc rotor under certain condition. The general form of the transient heat balance equation can be expressed as;

$$[B]\{\dot{u}\} + [R]\{u + T_{abs}\}^4 = \{P\} + \{N\} \tag{2.5}$$

Where;

$[B]$ = Heat capacity matrix

$\{\dot{u}\}$ = du/dt

$[R]$ = Radiation exchange matrix

T_{abs} = Temperature offset from the absolute required for radiation calculation

$\{P\}$ = Vector of constant applied of heat flow

$\{N\}$ = Vector of temperature dependent heat flow

In the steady-state case, this equation can be extensive nonlinear owing to radiation and temperature dependent material properties and boundary conditions. For the solution of this equation nonlinear iterations is required.

2.7 Finite Element Analysis

2.7.1 Introduction

Finite Element Analysis can be expressed as numerical solution to a specific field quantity problem by cutting a structure into several elements and describing the behavior of each element in a simple way. It useful for problem with complicated geometry, loading and material properties. This analysis use numerical technique to finding the approximate solution for partial differential equation and integral equation. By eliminating the differential equation completely and rendering the partial differential equations into the approximation system, this solution method can be solved.

This finite element analysis was used to predict the performance of and behavior of the disc rotor and calculate the safety margin. It also able to finds the weakness of the design disc rotor accurately. From this analysis also function as suitable method to solve partial differential equations in thermal stress analysis of brake disc rotor. The combination of computational and experiment methods was used to correlate and validate the result of thermo mechanical model with respect to brake analysis.

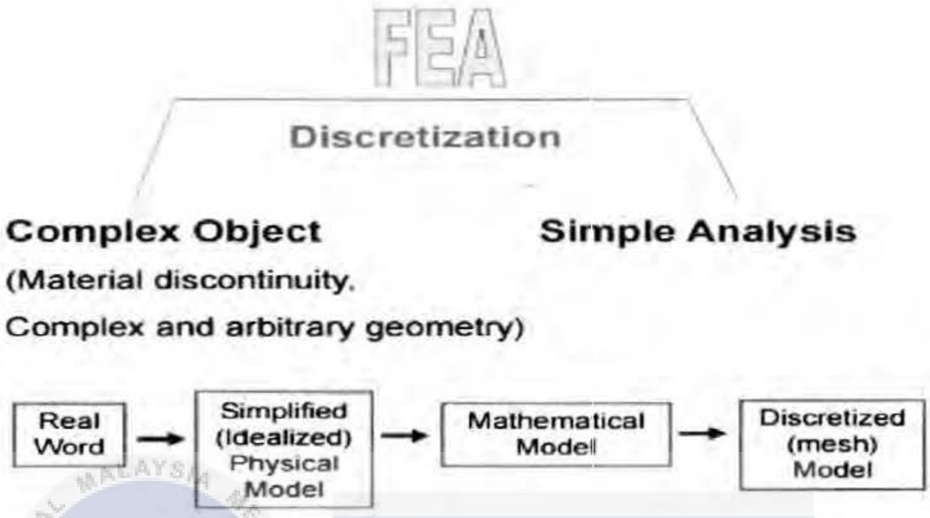


Figure 2.14: Show the FEA processes from the real object into modeling object

(Source: https://www.slideshare.net/tarungehlot1/introduction-to-finite-element-analysis)

There are many application of finite element analysis widely used in mechanical engineering. The heat transfer, biomechanics, fluid flow and etc. is the example of common application of finite element analysis. This analysis software provides a wide range of simulation options for controlling the complexity of both modeling and a system. By using finite element analysis as an application to test the initial prototype design, it significantly improved engineering designs.

2.7.2 ANSYS

Swanson Analysis System, Inc (SASI) was creates by John A. Swanson in 1970's. The main objective of this company is to develop and market finite element analysis software for structural physics that could simulate static, dynamic and thermal problems. The new owner took SASI leading software and it renames as ANSYS the new company name. ANSYS can be used to simulate interactions because it general purpose software. There are functions of ANSYS that have been used by engineers to simulate test of:

- Heat transfer
- Fluid dynamic
- Vibration
- Structural
- Electromagnetic

In this research, ANSYS was used to determine the heat transfer in disc brake rotor. It can show the weakness point of disc brake rotor by meshing the model of solid work into this software. One of the most important things this software able to improve the design of disc brake rotor by testing and quickly analyses the 3D designs of disc rotor to find their weakness. The results of this software will be reviewed as graphical and numerical.

2.7.3 Finite Element Modeling

The finite element modeling was used the full model scale of brake disc rotor for the simulation analysis. The auto mesh was used to generate mesh model due to the complexity of construction. When the number of nodes is increased, the mesh model is limited due to the computer performance of processing time. Through the calculation of both side of the surface area of the brake disc model, the symmetrical boundary condition can be defined. The value of function or unknown function at a set of a nodal point can be expressed in term of a finite element number of degree of freedom. This finite element was used to be aware of the limitation of the brake disc rotor modeling.

2.7.4 Finite Element Analysis Stage

The first step to do finite element analysis stage is by set up the transient analysis and steady state condition type of the analysis and all the properties of brake disc material must be applied. The properties of brake disc materials are:

- Thermal conductivity
- Density
- Specific heat
- Poison ratio

The second step is generates mesh to the model and apply heat flux to brake disc model. The processing time will be longer if the model had complex design. In order to predict the temperature distribution over the disc during braking process, the transient and steady state condition must be applied. After that, thermal stress analysis was performed by applying the heat flux on the brake disc surface as thermal loads and using the higher of number of global size of meshing. That will keep the processing time shorter and the number of design variable must be kept in acceptable range. Third step is the heat fluxes are assigned to the elements within the contact zone (every time step) during the simulation. The fourth step is the location of the contact zone was determined by the relative position of the disc and pad from the calculation of the deceleration rate of the disc. Lastly, the distance between adjacent nodes was calculated by apply heat flux at every contact nodes. Then, the time taken to rotate the nodes is taken as the time increment.

2.7.5 Review of Previous Research

There a lot of research about finite element analysis of brake disc rotor. Mostly, the research paper that has been found explained about the thermal behavior of brake disc rotor. The paper that has been founded was review in this section. There several information that can be used as a reference to this final year project. Valvano & Lee (2000) did a study on the technique to determine the thermal distortion of a brake rotor. The thermal distortion of a brake rotor can affect the system response and brake judder propensity. The accurate prediction of a thermal can help in the designing of a brake disc. Belhocine & Bouchetara (2013) did a study on title temperature and thermal stresses of vehicle gray cast brake. That research to analyze the thermo mechanical behavior of the dry contact between the disc pads during the braking phase. The geometric design of disc brake rotor can affect the improvement of the cooling process of the disc rotor. Kajela Termesgen Deressa (2013) studied on thermal stress analysis of disc brake rotor by finite element method. It investigated the temperature and thermal stress response of gray cast iron disc brake during first braking phase. The result show that overheating of brake rotor will leads to rupture, crack initiation and fade of the brake. Nakatsuji (2002) studied on the initiation of hair-like cracks which formed round small holes in the flange of one-piece disc during overloading conditions. The study showed that thermally induced the cyclic stress strongly affects the crack affects the crack the initiation in the brake disc rotor.

CHAPTER III

METHODOLOGY

3.1 Overview

Finite element analysis was used to predict the thermal stress analysis and thermal distribution behavior inside the brake rotor. By applying the physic theory on the brake disc rotor, the temperature rising while braking process can be analyzed. During the analysis, all braking parameters were set up to fixed value based on the value that has been state at literature review. The parameter includes of Formula Varsity specification, material properties of the rotor and the dimension of the disc rotor. In order to stop the vehicle, a certain amount of kinetic energy was transferred to the disc rotor through the brake to dissipate the energy. The brakes will convert kinetic energy to thermal energy via friction between brake pads and disc rotor. The analysis of the brake temperature required of the amount of total energy absorbed by the front brake disc rotor.

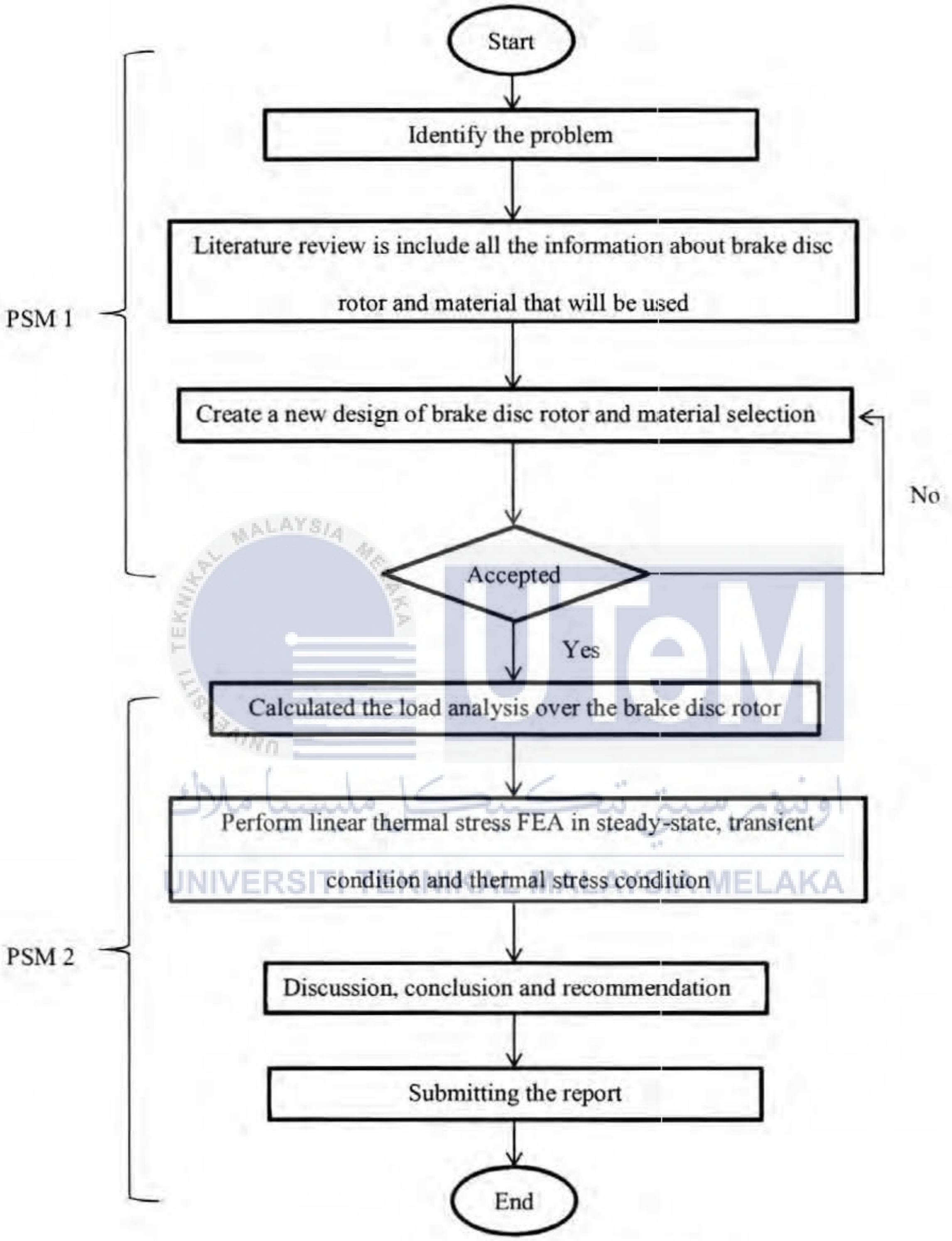


Figure 3.1: Overall process flow chart

3.2 Assumption in Heat Input Calculation

There are several assumptions that have been made to simplify the analysis and it allowed the reasonable output is obtained from the result of the simulation. The assumptions that can be made are:

- Assumed that the brake disc rotor in a stationary while the pads are in rotation.
- At the surfaces of brake disc rotor, the heat flux is applied uniformly.
- The calculation of convective heat loss and transient condition based on the highest Formula Varsity velocity.
- The temperature of the variation of material properties is ignored.
- The heat loading is assumed as ramp load decreasing in linear relation.

3.3 Formula Varsity Model

3.3.1 Introduction

Formula Varsity is a student design competition organized by UTeM that challenges student to design and manufacture formula style racing car in real track. These events inspired and similar like formula style racing car such as Formula SAE.

Figure 3.2: Formula Varsity car

(Source: http://brokenterompah.blogspot.my/)

The prototype race car that has been designed by student will be evaluated before the race is start. At beginning of competition, the racing car will be checked for rule command. The braking abilities are the one that have been checked before the racing car is allowed to compete in the racing event. The racing cars must have two hydraulic brakes with their own type of brake that has been designed. In this design of Formula Varsity, there is no weight restriction but the average competitive is usually less than 250 kg.

3.3.2 Dimension

Table 3.1: Formula SAE car specification

(Source: hhtp://sae.org/students/fsae-designspecs.xls)

Dimensions	Front	Rear
Overall length, width, height	2338mm long,1476mm wide, 1404mm high	
Wheelbase	1676mm	
Track width	1410mm	1475mm
Weight with 68kg driver	121kg	138kg

Brake System/ Hub & Axle	Front	Rear
Rotors	Floating, Cast iron, Hub mounted, 205mm dia. vented	Outboard, 260 mm dia x 10mm carbon ceramic
Master Cylinder	Student built 22mm bore front / 19mm bore rear with driver adjustable bias bar	
Calipers	48mm dia, opposing piston, fixed mtg	Dual piston, 25mm dia., floating
Hub Bearings	Tapered roller bearings. Separate spring loaded rubber lip seal	Single 5205dbl row ang contact bearing with integral seal
Upright Assembly	CNC 7075-Al, integral caliper mount	Weldment, 4130 sheet, heat treated , shot peened
Axle type, size & material	Fixed spindle, 28mm dia. 4130 steel normalized	Rotating axle, 52mm OD x 2.5mm wall, 4340 steel, RC40

3.3.3 Brake Disc Rotor

In order to produce the new design of disc brake rotor for Formula Varsity, the current design must be study first. For this project, the current design have used motorcycle single brake disc rotor. That means, the new ideas for this concept must be followed by using motorcycle single brake disc rotor as a new design. This type of disc brake rotor has been chooses because it want to reduce the overall weight of the Formula Varsity racing car. Figure 13 show the current design that has been used for this project:

Figure 3.3: Current design of disc brake rotor

(Source: http://www.ferodoracing.com)

The dimension of disc brake rotor must suitable and fit to use as a braking system. Table 3.2 show the brake disc rotor specification for Formula Varsity racing car used in this project.

Table 3.2: Brake disc rotor specification

Disc Geometry of Formula Varsity Racing Car	
Disc outer diameter	220 mm
Disc inner diameter	50 mm
Disc thickness	5 mm
Cross drilled hole diameter	7 mm

3.3.4 Disc Material

In this section, there two type of disc material has been compared which is Compacted Graphite Iron and Gray Cast Iron. The both material has advantages and disadvantages characteristic. The selection of material has been chosen based on the most advantages characteristic in sentence case. Table 3.3 show the comparison between Compacted Graphite Iron and Gray Cast Iron based on their properties material.

Table 3.3: Comparison between Compacted Graphite Iron and Gray Cast Iron

(Source: http://www.classguss.de)

Properties \ Material	**Compacted Graphite Iron (GJV450)**	**Gray Cast Iron (BS220)**
Mass density	7100 kg/m^3	7200 kg/m^3
Thermal conductivity	38 W/m.K	48 W/m.K
Specific Heat	475 J/kg.K	430 J/kg.K
Poisson Ratio	0.27	0.265
Young's Modulus	150 Gpa	105 Gpa
Coefficient of thermal expansion	1.1 x 10^{-5}m/(m.K)	1.29996 x 10^{-5}m/(m.K)
Service Temperature	-160°C - 550°C	150°C - 450°C
Yield Strength, S_y	415 MPa	200 MPa

The Compacted Graphite Iron has been chosen as disc material in this project based on the comparison from Table 3.3. From the Table 3.3 it can be conclude that the compacted graphite iron are more excellent material than gray cast iron based on their characteristic. Others reason why this material was selected because of it has the ability to dissipate heat, increased dampening properties and the internal porosity solidifies in a manner similar to gray cast iron with the strength of ductile iron that allows complicated castings.

3.4 Brake Disc Rotor Modeling

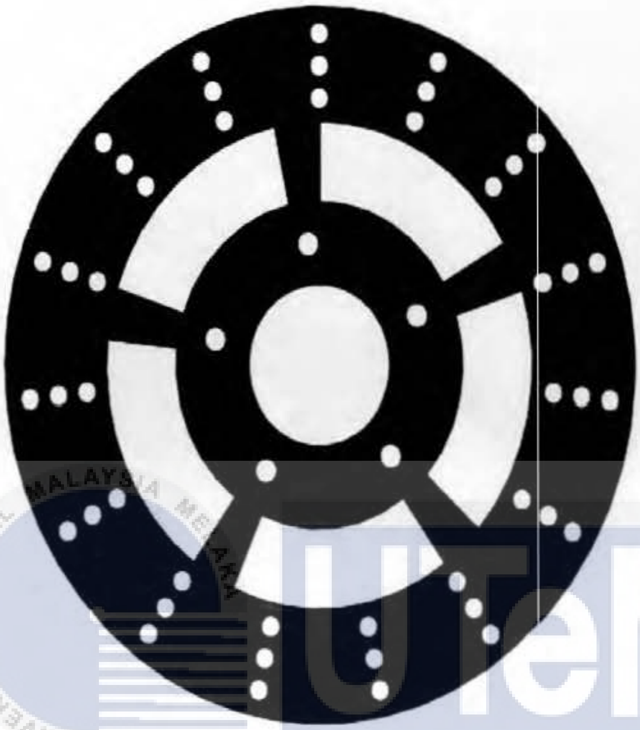


Figure 3.4: 1st design of disc brake rotor

Figure 3.5: 2^{nd} design of disc brake rotor

Figure 3.4 and 3.5 show the two designs of disc brake rotor modeling by using SolidWork software. The differences between those two are the drilled holes at the disc brake rotor. The reason is because the effected of thermal stress can be seen by difference design of model. The 1^{st} design drilled holes was builds with straight path while 2^{nd} design with curve path. The design will be select based on the ability to dissipate the heat faster than another design.

3.5 Calculation to Determine Weight of Disc Brake Rotor

Figure 3.6: Design brake disc that has been choose

Based on the Figure 3.6, the calculation can be divided into 4 parts that are:

1) Area of cross-drilled holes, A_h

2) Area of brake surface, A_s

3) Area of inner cooling vents, A_i

4) Area of part inside the cooling vents, A_p

For area of cross-drilled holes, A_h:

$$A_h = \text{Total no. of holes} \times \frac{\pi d^2}{4} \quad (3\text{-}1)$$

For area of brake surface, A_s :

A_s = Area of outer diameter of disc rotor – area of outer cooling vanes – A_h

$$= \frac{\pi d^2}{4} - \frac{\pi d^2}{4} - A_h \quad (3\text{-}2)$$

For area of inner of cooling vanes, A_i:

A_i = Area of inner cooling vanes – area of inner diameter of disc rotor

$$= \frac{\pi d^2}{4} - \frac{\pi d^2}{4} \quad (3\text{-}3)$$

For this design, the part that contain inside the cooling vents is five parts. Each part is 18° which can be calculated as 5×18° = 60° for all disc brake rotors. So for area of part inside the cooling vanes, A_p:

A_p = Area of outer cooling vanes – area of inner cooling vanes - $\frac{60°}{360°}$

$$= \frac{\pi d^2}{4} - \frac{\pi d^2}{4} - \frac{60°}{360°} \quad (3\text{-}4)$$

For total surface area by using this equation, A_T:

$$A_T = A_s + A_i + A_p \tag{3-5}$$

The volume should be determined to calculate the mass for this disc brake rotor by using this equation:

$$\text{Volume, V} = A_T\,(T_{disc}) \tag{3-6}$$

Where,

T_{disc} = the thickness of the disc brake rotor

By using density equation, $\rho = \frac{m}{V}$ can be rearrange to calculate the mass of disc brake rotor which is:

$$m = \rho V \tag{3-7}$$

3.6 Thermal flow calculation

By determine the kinetic energy, thermal flow can be calculated and followed by braking energy, braking surface and finally heat flux.

$$\Delta E = \frac{mv^2}{2} \qquad \text{(Gotowicki, 2005)} \qquad (3\text{-}8)$$

Where,

m = mass of formula varsity car

v = maximum speed of formula varsity car

For this case, the braking energy is act on single rear wheel only which is:

Braking energy or work, L = Q

$$= \frac{0.50(1.1)(\Delta E)}{2} \qquad \text{(Gotowicki, 2005)} \qquad (3\text{-}9)$$

When braking, the heat will produced and it dissipated to the surrounding. The thermal flow is occurs during this case. The thermal equation can be express, q:

$$q = \frac{Q}{\Delta T} \qquad (3\text{-}10)$$

After determine the thermal flow equation, the heat flux can be calculated. To calculate the heat flux, equation of the $q_{specific}$ is assumed same as the equation for determined the heat flux.

$$\text{Heat flux, } q_{specific} = \left[\frac{\frac{q}{s_{flux}}}{5}\right] \tag{3-11}$$

The value of braking surface, s_{flux} must be determined before proceed to the heat flux calculation. That is because the value of braking surface is needed in the heat flux equation. So, the heat flux equation can be express as:

$$s_{flux} = \pi({R_D}^2 - {R_{i-outer}}^2) - \text{(Area of cross-drilled holes)} \tag{3-12}$$

3.7 Heat Transfer Equation

In order to determine the Reynolds number, Re there is two equations that has been used in this case. The equation can be used only when the heat transfer is laminar flow. To determine whether the flow is laminar or turbulent flow, if the Reynolds number is less than 2.4×10^5 it is laminar flow.

While for turbulent flow there is equation for Reynolds number that has been used:

$$\mathrm{Re} = \frac{\omega_{disc}\ {R_d}^2}{\nu} \tag{3-13}$$

Where,

ω_{disc} = Angular speed of disc brake rotor

R_d = Radius of the disc brake rotor

ν = Viscosity of air (1.6×10^{-5})

$$\mathrm{Re} = \frac{\rho_a\ d_h\ V_{average}}{\mu_a} \tag{3-14}$$

Where,

ρ_a = Density of air (1.293 kg/m^3)

d_h = Hydraulic diameter

$V_{average}$ = Average air velocity

μ_a = Dynamic air viscosity ($1.86 \times 10^{-5}\ Ns/m^2$)

To determine the heat transfer coefficient for boundary, there are four equations that related to the calculation of this project which is:

$$h_R = 3.974 \left(\frac{k_a}{D_{Dr}}\right) \text{Re}^{0.55} \qquad \text{(Huang and Chen, 2006)} \qquad (3\text{-}15)$$

Where,

k_a = Thermal conductivity of air (0.02624 W/m.K)

D_{Dr} = Diameter of outer disc brake rotor

Re = Reynolds number

$$h_R = 0.70 \left[\frac{k_a}{D_D}\right] \text{Re}^{0.55} \qquad (3\text{-}16)$$

Where,

k_a = Thermal conductivity of air (0.02624 W/m.K)

D_D = Diameter of outer disc brake rotor

Re = Reynolds number

$$h_R = 1.861(\text{Re Pr})^{1/3}\left(\frac{d_h}{l}\right)^{0.33}\left(\frac{k_a}{d_h}\right) \tag{3-17}$$

Where,

Re = Reynolds number

Pr = Prandtl number (0.72) (Johari, 2008)

d_h = Hydraulic diameter

l = Depth of cross-drilled holes

k_a = Thermal conductivity of air (0.02624 W/m.K)

The hydraulic diameter, d_h can be determine by using this equation:

$$d_h = \frac{4\,(12\times area\ of\ one\ cross-drilled\ holes)}{2(12\times diameter\ of\ one\ cross-drilled\ holes)}$$

$$d_h = \frac{4\left(12\times\frac{\pi {d_{holes}}^2}{4}\right)}{2(12\times 2\pi\times R_{holes})} \tag{3-18}$$

Where,

d_{holes} = Diameter of one-cross drilled holes

R_{holes} = Radius of one-cross drilled holes

The next Equation for the cooling vanes parts, the equation for hydraulic diameter, d_h is:

$$d_h = \frac{4(area\ of\ \frac{1}{5}\ parts)}{2(circumferences\ of\ \frac{1}{5}\ parts)}$$

$$d_h = \frac{4\left(\frac{60^\circ}{360^\circ}\right)\left(\frac{\pi d_{ov}{}^2}{4}\right)-\left(\frac{\pi d_{id}{}^2}{4}\right)}{2\left[\left((R_{ov}-R_{iv})\times 4\right)+\left(\frac{60^\circ}{360^\circ}\times 2\pi\times R_{ov}\right)+\left(\frac{60^\circ}{360^\circ}\times 2\pi\times R_{iv}\right)\right]} \tag{3-19}$$

Where,

d_{ov} = Diameter of outer cooling vanes

d_{id} = Diameter of inner disc rotor

R_{ov} = Radius of outer cooling vanes

R_{iv} = Radius of inner cooling vanes

This next equation was used to determine the average of air velocity, $V_{average}$:

$$V_{average} = \frac{V_{in}\left(1+A_{in}/A_{out}\right)}{2} \tag{3-20}$$

Where,

V_{in} = Velocity of air into cooling vanes

V_{out} = Velocity of air out the cooling vanes

A_{in} = Area of air into the cooling vanes

A_{out} = Area of air out cooling vanes

$$V_{in} = 0.0158\, N_{disc}\left({D_D}^2 - {D_{i-vanes}}^2\right)^{0.5} \tag{3-21}$$

Where:

N_{disc} = Disc brake rotor speed

D_D = Diameter of outer disc brake rotor

$D_{i-vanes}$ = Diameter of inner cooling vanes

CHAPTER 4

LOAD ANALYSIS

4.1 Theory Calculation for Brake Disc Rotor

The calculation for brake disc rotor can be divided into two types which are heat transfer coefficient and heat flux calculation. The heat transfer coefficient was calculated to determine the amount of heat transferred in a brake disc rotor. The heat transfer can be calculated by determine the Reynolds number and followed by heat transfer formula. Heat flux calculation was calculated to determine the rate of heat energy transfer through the surface of brake disc rotor. The calculation was divided into five sections to make the calculation easier.

4.2 Specification of Performances and Dimensions

Formula Varsity race car event was followed the same regulation by Formula SAE. So, the performances and dimension of racing car should be quite same. In order to calculate the value for braking time and stopping distance, the specification and dimension of University of Toronto Formula Motorsport car was chosen as references.

Table 4.1: Specification of the University of Toronto Formula Motorsport

(Source: http://fsae.utoronto.ca/2002/car.html)

Performances	
0-100 km/h	2.89 seconds
Maximum Speed	160 km/h
Lateral Acceleration	1.82 g
Braking Acceleration	1.6 g
Dimensions	
Overall Length	2766 mm
Overall Height	1058 mm
Wheelbase	1536 mm
Front Track	1193mm
Rear Track	1168 mm
Inertial Coefficient	1.1
Weights	240 kg with 68 kg driver
Rims	Kodiak Custom alloy (7.0 × 13)
Tyres	20 × 7 Goodyear Eagle

4.3 Braking Method

The braking method used by previous researcher considered the common passenger car. The braking schedule consist of braking time, number of braking, time taken, maximum speed of vehicle and deceleration value which is when vehicle braked. The heat flux is occurred when the brake pedal was applied or pressed. The heat flux will produce at the surface of disc rotor. By using data or information from Table 4.1, the heat flux on the surface of disc rotor and all convection of heat transfer coefficient can be determined.

As we can see from the brake schedule, the maximum speed of vehicle is 160km/h. The braking acceleration is equal to 1.6 g = 15.7 m/s^2 which is the deceleration of vehicle based on data from Toronto Formula Motorsport Car performances specification. From the table, the maximum speed of the formula car can be determined.

$$\text{Maximum Speed, } v = \frac{160 \times 1000}{360}$$

$$= 44.44\ \mathrm{m/s}$$

The stopping distance of formula car can be calculated to show when the brake energy is applied, how far it will stop moving. The braking time also must be determined to see how much time taken for the car to stop after the brake was applied.

Stopping distance, $\Delta x = \frac{v^2}{2a}$

$$= \frac{44.44^2}{2(15.7)}$$

$$= 62.90 \text{ m}$$

Braking Time, $\Delta t = \frac{2\Delta x}{v}$

$$= \frac{2(62.90)}{44.44}$$

$$= 2.83\ s$$

4.4 Weight for disc Brake Rotor

The weight of disc brake rotor can be calculated by determine the dimension of brake disc rotor first. The geometrical dimension of the disc brake rotor has been shown in the Table 4.2.

Table 4.2: Geometrical dimension for brake disc rotor design

Geometrical dimension	
Disc outer diameter	0.220 m
Disc inner diameter	0.050 m
Disc thickness	0.005 m
Diameter of outer cooling vents	0.150 m
Diameter of inner cooling vents	0.100 m
Total number of cross-drilled holes	45
Density of Compacted Graphite Iron	7100 kg/m^3
Diameter of cross-drilled holes	0.007 m

By using the Eq. on chapter 3.5:

From Eq. (3-1)

For area of cross-drilled holes, $A_h = 45 \times \frac{\pi(0.007)^2}{4}$

$$= 1.73 \times 10^{-3}\ m^2$$

From Eq. (3-2)

For area brake surface, $A_s = \frac{\pi\ (0.22)^2}{4} - \frac{\pi(0.15)^2}{4} - 1.73 \times 10^{-3}$

$$= 0.01867\ m^2$$

From Eq. (3-3)

Area for inner cooling vents, $A_i = \frac{\pi\,(0.1)^2}{4} - \frac{\pi(0.05)^2}{4}$

$$= 0.005891\ m^2$$

From Eq. (3-4)

Area for part inside the cooling vents, $A_p = \frac{\pi\,(0.15)^2}{4} - \frac{\pi(0.1)^2}{4} - \frac{60°}{360°}$

$$= 0.001797\ m^2$$

From Eq. (3-5)

Total surface area, $A_T\ =\ 0.01867 + 0.005891 + 0.001797$

$$=\ 0.026358\ m^2$$

From Eq. (3-6)

The volume, v = 0.026358 (0.005)

$$= 0.00013179\ m^3$$

$$= 1.379\ \times 10^{-4}\ m^3$$

From Eq. (3-7)

The mass of disc brake rotor, $m = 7100\ (1.3.79\ \times 10^{-4})$

$$= 0.936\ kg$$

The mass of disc brake rotor current design is 1.6 kg based on information from Specification of the University of Toronto Formula Motorsport and determined by using the weighing using weight scale. While from the calculation, the mass of disc brake rotor is 0.936 kg. The value of mass from the calculation reduces to 40% from the current design. The weight from calculation was used because it more suitable for this project.

4.5 Thermal Flow Calculation

Thermal flow calculation can be calculated by determined the kinetic energy that appears to stop the maximum speed of the vehicle. The kinetic energy can be determined by using the Eq. (3-8) from chapter 3. The value of parameter m is the vehicle mass while v is the vehicle maximum speed

Kinetic Energy, $\Delta E = \frac{mv^2}{2}$

$$= \frac{172(44.44)^2}{2}$$

$$= 170 \text{ kJ}$$

To calculate the braking energy, the Eq. (3-9) in chapter 3 was used which is:

Braking Energy, L (for single rear wheels only)

$L = Q = \frac{50\% \ (1.1)(\Delta E)}{2}$ (Gotowicki, 2005)

$$= \frac{0.50(1.1)(170)}{2}$$

$$= 46.75 \text{ kJ}$$

To calculate the thermal flow, the Eq. (3-10) was used which is:

Thermal Flow, $q = \frac{Q}{\Delta t}$

$$= \frac{46.75}{2.83}$$

$$= 16.52 \text{ kJ/s}$$

Next for braking surface, the Eq. (3-12) was used:

Braking Surface, S_{flux}

$$S_{flux} = \pi({R_D}^2 - {R_i}^2) - \text{Area of cross-drilled holes}$$

$$= \pi(0.110^2 - 0.075^2) - 1.73 \times 10^{-3}$$

$$= 0.0186 \ m^2$$

Equation (3-11) was used to calculate the heat flux of the surface disc brake rotor:

$$\text{Heat flux, } q_{specific} = \left[\frac{\frac{q}{S_{flux}}}{5}\right]$$

$$= \left[\frac{\frac{16.52}{0.0186}}{5}\right]$$

$$= 177.63 \text{ kW}/m^2$$

The value for thermal flow in disc brake rotor is 16.52 kJ/s while the value for heat flux of the surface disc brake rotor is 177.63 kW/m^2. This both value will be used in the steady-state analysis and transient analysis.

4.6 Heat Transfer calculation

In order to start the calculation of heat transfer, the disc brake rotor has been divided into four parts same as chapter 3.5:

I. Heat transfer coefficient for disc brake surface

II. Heat transfer coefficient for outer diameter of disc

III. Heat transfer coefficient for cross-drilled holes

IV. Heat transfer coefficient for cooling vanes of disc

4.6.1 Heat Transfer Coefficient for Disc Brake Surface

The angular speed of tyre and disc rotor speed must be determined first before heat transfer coefficient can be calculated.

Initial speed, v = $44.44\ m/s$

Radius of tyre, $R_{tyre} = 0.4702\ m$ (Radial tyre type)

The angular speed of tyre, $\omega_{tyre} = \frac{v}{R_{tyre}}$

$$= \frac{44.44}{0.4702}$$

$$= 94.51\ s^{-1}$$

The angular speed of tyre is assumed has same value as angular speed of disc:

So, $\omega_{tyre} = \omega_{disc}$

From this equation, $\omega_{disc} = \frac{2\pi(N_{disc})}{60}$ the value of disc rotor speed (N_{disc}) can be calculated by rearrange that equation as shown below:

$$N_{disc} = \frac{\omega_{disc}(60)}{2\pi}$$

$$= \frac{94.51(60)}{2\pi}$$

$$= 902.50 \text{ rpm}$$

Based on Eq. (3-13), Reynolds number can be write equal to:

$$\mathrm{Re} = \frac{\omega_{disc}\ {R_d}^2}{v} \qquad \mathrm{Re} < 2.4 \times 10^5 \text{(laminar flow)}$$

$$= \frac{(94.51)(0.110)^2}{1.6 \times 10^{-5}}$$

$$= 71.47 \times 10^3$$

From the Eq. (3-15), the convection of heat transfer coefficient for disc brake surface is:

$$D_{Dr} = 0.220\ m \quad , \quad Re = 71.47 \times 10^3$$

$$h_R = 3.974 \left(\frac{k_a}{D_{Dr}}\right) \mathrm{Re}^{0.55}$$

$$h_R = 3.974 \left(\frac{0.02624}{0.220}\right) (71.43 \times 10^3)^{0.55}$$

$$h_R = 221.52\ W/m^2\mathrm{K}$$

4.6.2 Heat Transfer Coefficient for Outer Diameter of Disc

Based on the Eq. (3-13), the Reynolds number is equal to:

$R_d = 0.110\ m$ $\omega_{disc} = 94.51\ s^{-1}$

$$\text{Re} = \frac{\omega_{disc}\ {R_d}^2}{v}$$

$$= \frac{(94.51)(0.110)^2}{1.6 \times 10^{-5}}$$

$$= 71.47 \times 10^3$$

$$\therefore \text{Re} = 71.47 \times 10^3$$

By using Eq. (3-16) to determine the convection heat transfer coefficient for outer diameter of disc brake rotor:

$D_d = 0.22\ m$ $\text{Re} = 71.47 \times 10^3$

$$h_R = 0.70 \left[\frac{k_a}{D_D}\right] \text{Re}^{0.55}$$

$$= 0.70 \left[\frac{0.02624}{0.22}\right] 71.47 \times 10^{3^{0.55}}$$

$$= 39.03\ W/m^2K$$

4.6.3 Heat Transfer Coefficient for Cross-Drilled Holes

For this part of calculation is quite hard, the disc rotor has been divided into five symmetrical section to make calculation easier. 1/5 of this part will be representing of the whole part in this disc brake rotor. The area for cross drilled-holes must be determined first and the calculation for the heat transfer coefficient for cross-drilled holes can be calculated after that. The Eq. (3-20) has been used and A_{in} is assumed equal to A_{out}.:

$$V_{average} = \frac{V_{in}\left(1+A_{in}/A_{out}\right)}{2}$$

$$V_{average} = V_{in}\left(\frac{1+1}{2}\right)$$

$$V_{average} = V_{in}$$

By using the Eq. (3-21), the value of V_{in} equal to:

N_{disc} = 902.50 rpm, D_D = 0.22 m, $D_{i-vanes}$ = 0.15 m

$$V_{in} = 0.0158\, N_{disc}\left({D_D}^2 - {D_{i-vanes}}^2\right)^{0.5}$$

$$V_{in} = 0.0158\,(902.50)\,(0.22^2 - 0.15^2)^{0.5}$$

$$V_{in} = V_{average} = 2.29\ m/s$$

By using Eq. (3-18), the hydraulic diameter can be determined:

$d_{holes} = 0.007$ m, $R_{holes} = 0.0035$ m

$$d_h = \frac{4\left(12 \times \frac{\pi(0.007)^2}{4}\right)}{2(12 \times 2\pi \times 0.0035)}$$

$d_h = 0.0035$ m

The next Eq. (3-14) was used to determine Reynolds number by using this value:

$d_h = 0.0035$ m, $V_{average} = 2.29\ m/s$

$$\mathrm{Re} = \frac{\rho_a\, d_h\, V_{average}}{\mu_a}$$

$$\mathrm{Re} = \frac{1.293\ (0.0035)(2.29)}{1.86 \times 10^{-5}}$$

$\mathrm{Re} = 557.17 < 10000$ (laminar flow)

Lastly, the heat transfer coefficient can be calculated by using Eq. (3-17):

$\mathrm{Re} = 557.17$, $d_h = 0.0035$ m, $l = 0.005$ m

$$h_R = 1.861(\mathrm{Re\,Pr})^{1/3} \left(\frac{d_h}{l}\right)^{0.33} \left(\frac{k_a}{d_h}\right)$$

$$h_R = 1.861(557.17 \times 0.72)^{1/3} \left(\frac{0.0035}{0.005}\right)^{0.33} \left(\frac{0.02624}{0.0035}\right)$$

$h_R = 89.45\ W/m^2K$

4.6.4 Heat Transfer Coefficient for Cooling Vanes of Disc

From the Eq. (3-21), the value of $V_{average}$ is equal to V_{in} therefore:

$N_{disc} = 902.50$ rpm, $D_d = 0.15$ m, $D_{i-vanes} = 0.10$ m

$$V_{in} = 0.0158\, N_{disc} \left({D_D}^2 - {D_{i-vanes}}^2\right)^{0.5}$$

$$V_{in} = 0.0158\ (902.50)\ (0.15^2 - 0.10^2)^{0.5}$$

$$V_{in} = V_{average} = 1.59 \text{ m/s}$$

Next, from the Eq. (3-19) the Reynolds number can be calculated by using information given:

$d_{id} = 0.100$ m, $d_{ov} = 0.150$ m, $R_{ov} = 0.075$ m, $R_{iv} = 0.050$ m

$$d_h = \frac{4\left(\frac{60^\circ}{360^\circ}\right)\left(\frac{\pi {d_{ov}}^2}{4}\right) - \left(\frac{\pi {d_{id}}^2}{4}\right)}{2\left[\left((R_{ov} - R_{iv}) \times 4\right) + \left(\frac{60^\circ}{360^\circ} \times 2\pi \times R_{ov}\right) + \left(\frac{60^\circ}{360^\circ} \times 2\pi \times R_{iv}\right)\right]}$$

$$d_h = \frac{4\left(\frac{60^\circ}{360^\circ}\right)\left(\frac{\pi (0.15)^2}{4}\right) - \left(\frac{\pi (0.10)^2}{4}\right)}{2\left[\left((0.075\ -\ 0.050) \times 4\right) + \left(\frac{60^\circ}{360^\circ} \times 2\pi \times 0.075\right) + \left(\frac{60^\circ}{360^\circ} \times 2\pi \times 0.050\right)\right]}$$

$$d_h = 8.505 \times 10^{-3} \text{ m}$$

To determined Reynolds number, Eq. (3-14) was calculated by using the value:

$d_h = 8.505 \times 10^{-3}$ m, $V_{average} = 1.59$ m/s

$$\text{Re} = \frac{\rho_a \, d_h \, V_{average}}{\mu_a}$$

$$\text{Re} = \frac{1.293\,(8.505 \times 10^{-3})(1.59)}{1.86 \times 10^{-5}}$$

$$\text{Re} = 940.06$$

Finally, by using Eq. (3-17) the heat transfer coefficient for cooling vanes can be determined. This is information from the previous calculation that has been used:

Re $= 940.06$, $d_h = 8.505 \times 10^{-3}$ m, $l = 0.005$ m

$$h_R = 1.861(\text{Re Pr})^{1/3} \left(\frac{d_h}{l}\right)^{0.33} \left(\frac{k_a}{d_h}\right)$$

$$h_R = 1.861(940.06 \times 0.72)^{1/3} \left(\frac{8.505 \times 10^{-3}}{0.005}\right)^{0.33} \left(\frac{0.02624}{8.505 \times 10^{-3}}\right)$$

$$h_R = 60.07\ W/m^2K$$

Table 4.3: Result from load analysis

Parts \ Value	Reynolds number, Re	Heat Transfer Coefficient, h_R
Disc Brake Surface	71.47×10^3	$221.52\ W/m^2$K
Outer Diameter of Disc Rotor	71.47×10^3	$39.03\ W/m^2K$
Cross-Drilled Holes	557.17	$89.45\ W/m^2K$
Cooling Vanes of Disc Rotor	940.06	$60.07\ W/m^2K$

4.7 Analysis Setup

4.7.1 Steady-State Analysis

In this section, steady-state analysis was performed to obtain the result. The step to setup the steady-state analysis was shown in picture below.

I. Open the ANSY and select Steady-State

II. Select Engineering Data

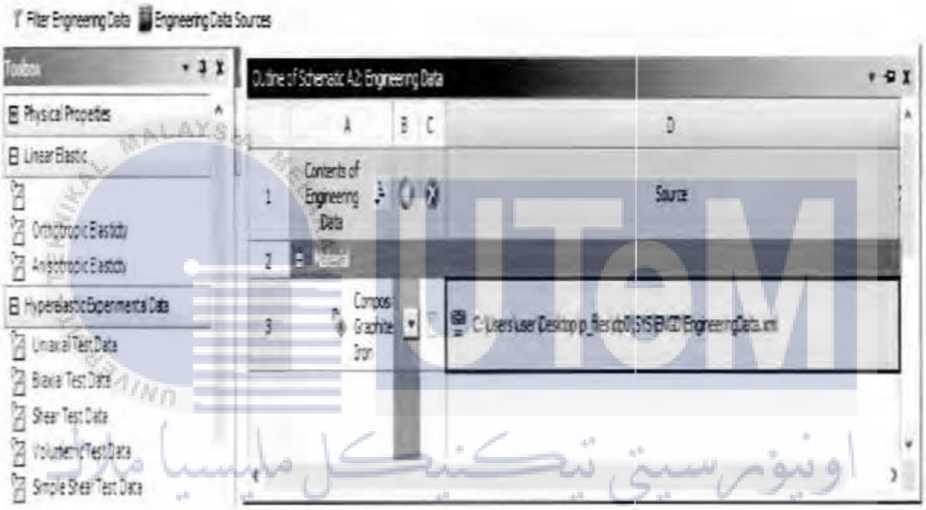
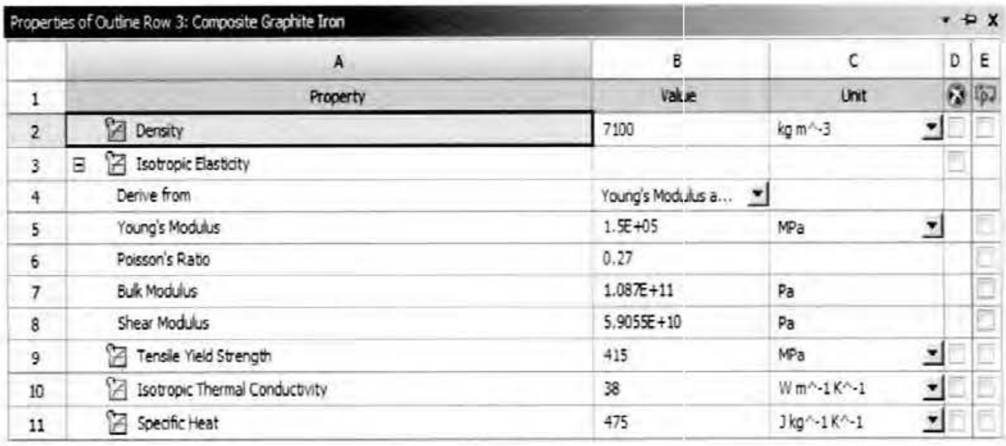


Figure 4.1: Engineering Data in Steady-State Analysis

By selecting the engineering data, the outline of schematic as Figure 4.1 will appeared when the engineering data source was click. In this engineering data, the material for Composite Graphite Iron is not provided. So the data have to added manually by referring Table 3.3 and then the data was add as new material. Rename the new material as Composite Graphite Iron and from the toolbox, drag and drop the desired properties.



	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7100	kg m^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Modulus a...			
5	Young's Modulus	1.5E+05	MPa		
6	Poisson's Ratio	0.27			
7	Bulk Modulus	1.087E+11	Pa		
8	Shear Modulus	5.9055E+10	Pa		
9	Tensile Yield Strength	415	MPa		
10	Isotropic Thermal Conductivity	38	W m^-1 K^-1		
11	Specific Heat	475	J kg^-1 K^-1		

Figure 4.2: Properties for Composite Graphite Iron

The value of desired properties must have been inserted as shown in Figure 4.2. There are important part such as Young`s Modulus and Poisson Ratio that we need to find by clicking Isotropic Elasticity. The unit also will auto inserted, but the unit need to change based on the information given.

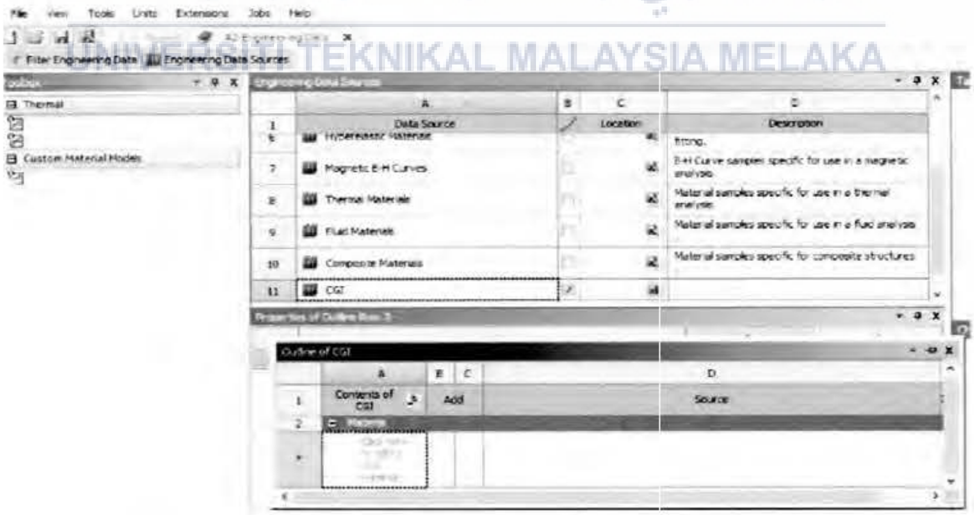


Figure 4.3: Composite Graphite Iron material added on the library

Based on the Figure 4.3, the material for Composite Graphite Iron has been added on the library by highlight the material name and export the Engineering Data (stored at desired location). Next step, by toggle the Data Sources and import the engineering data to browse the material. From the Figure 4.3, at the number 11 show the Composite Graphite Iron has been added into the library.

III. Open geometry by double click the icon

Figure 4.4: Import of geometry

The geometry design of disc brake rotor was import as shown in figure 4.4. Before that, the design of disc brake rotor from SolidWork must be saves in IGS file before inserted in the analysis. After the geometry was browse, the design of disc brake rotor will be shown in the analysis as shown in Figure 4.5. The selected area of brake disc has been finished in this section.

IV. Open model and mesh the design

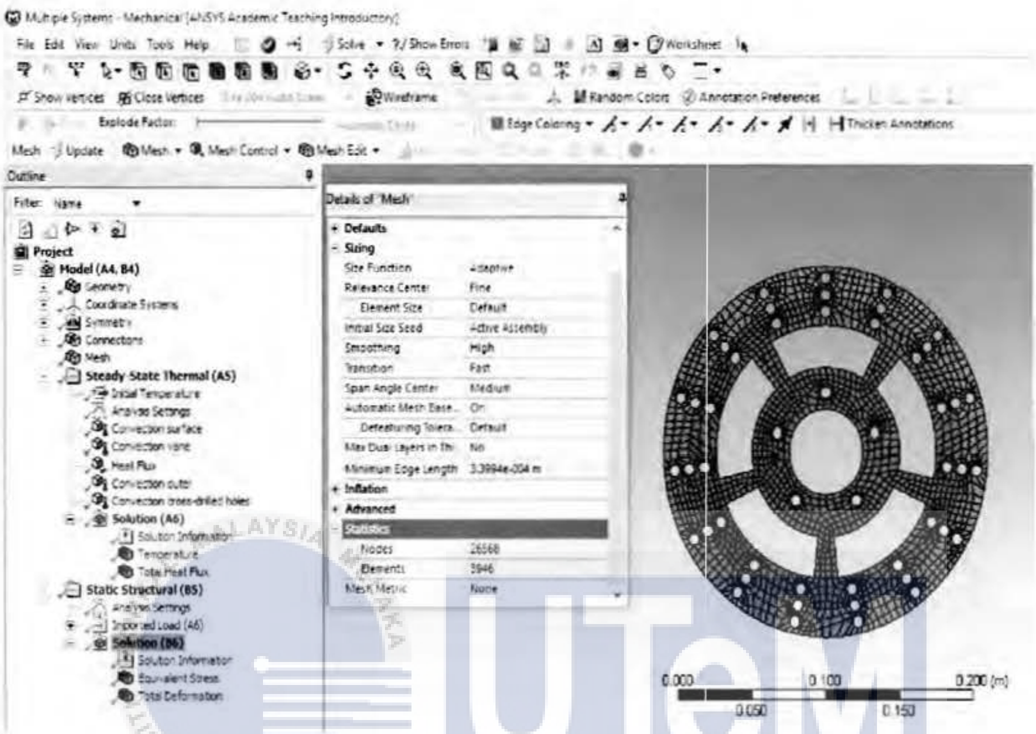


Figure 4.5: Process of meshing the design in steady-state analysis

From the figure above, it shown the design disc brake rotor was meshing and the details of the "Mesh" is provided. The details of "Mesh" have been adjusted to get the suitable nodes. The value of suitable nodes must be less than 30,000 and not to low such as below 20,000. After the suitable nodes have been satisfied, start meshing the design by click generates mesh.

V. Initial temperature

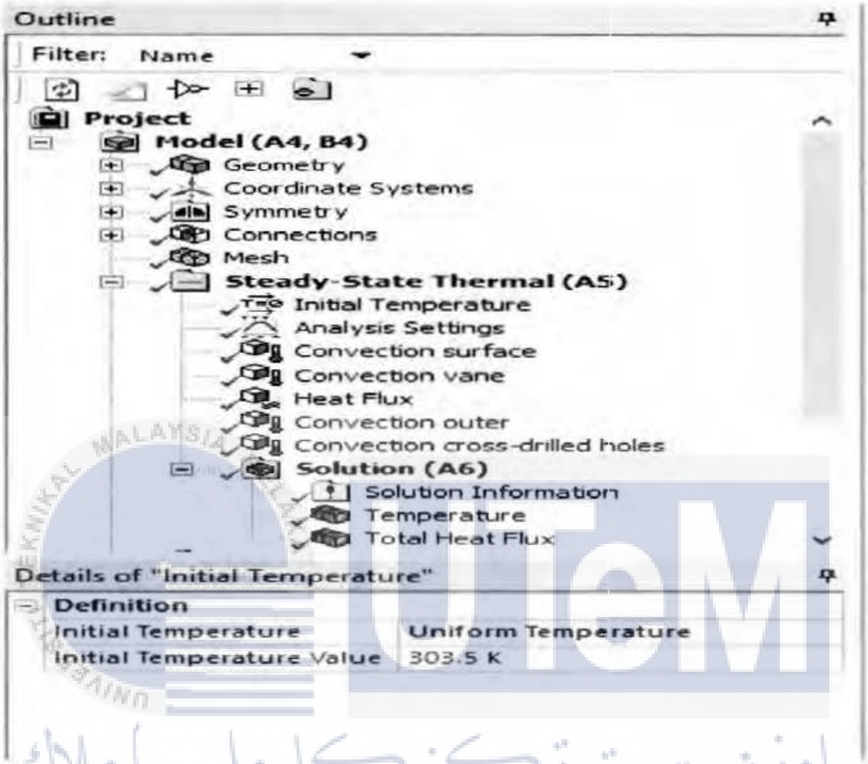


Figure 4.6: The initial Temperature for the steady-state analysis

Bases on Figure 4.6, the requirement that need to fill are initial temperature. The value for initial temperature was assumed same as room temperature which is 30°C that equal to 303.5 Kelvin. The uniform temperature was used to get the better result in this steady state analysis. After the details of initial temperature is complete, closed the information by enter the initial temperature value.

VI. Convection heat

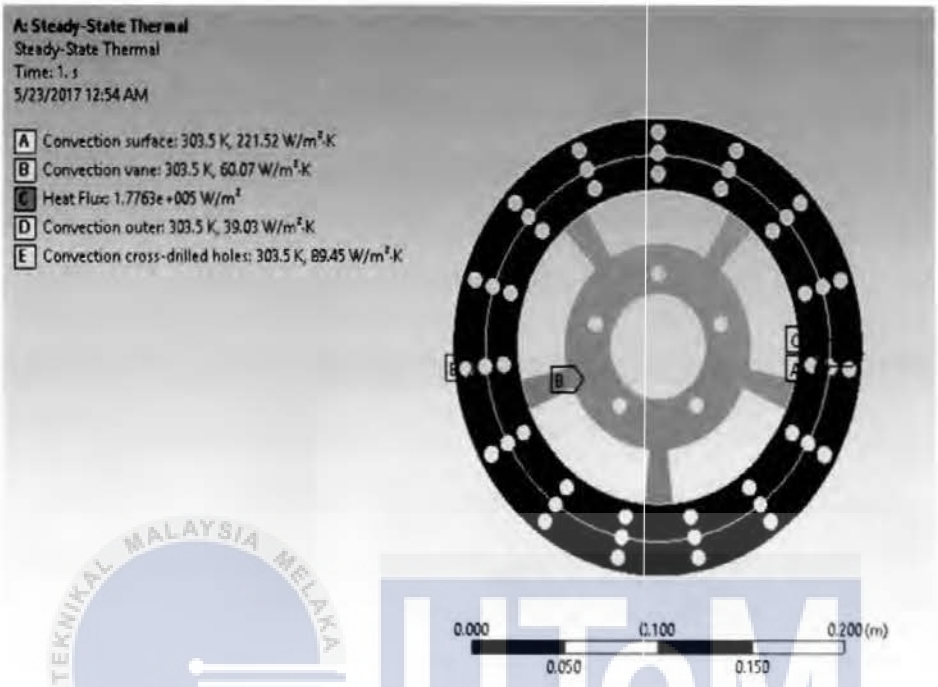


Figure 4.7: The heat convection in disc brake rotor design

From the Figure 4.7, it shows the heat convection in four places and one heat flux. The tag of alphabet of A, B, C, D and E represent the value of heat convection on that placed. The value of heat transfer coefficient for each requirement can be refers on Table 4.4. The requirement for steady-state thermal such as initial temperature, convection for all selected area and heat flux must be complete by fill each of the heat transfer coefficient After the entire requirement complete, click solve solution for temperature and its will show the results. A complete task will be show right icon(√) at the left side of requirement task.

4.7.2 Transient Analysis

In this section, transient analysis was performed to get the result. The step to setup the steady-state analysis was shown in picture below.

I. Open the ANSYS and select transient analysis as shown in Figure 4.8.

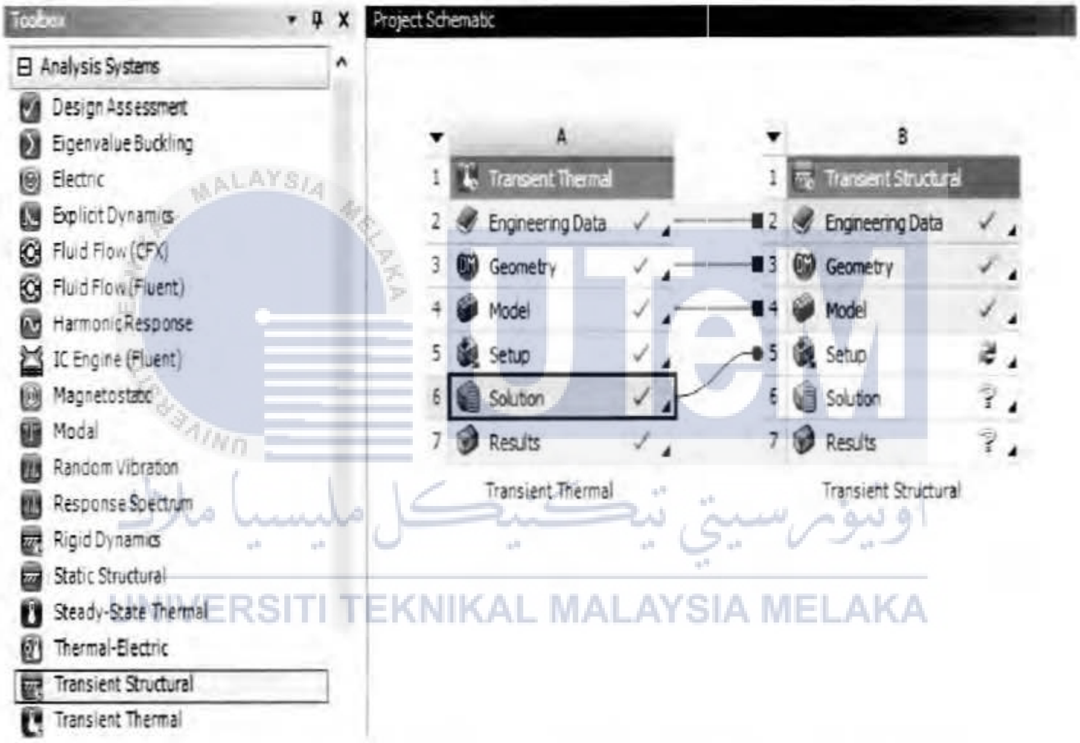


Figure 4.8: The analysis system of Transient Analysis of disc brake rotor

II. Step II until V of steady-state was repeated in this transient analysis.

III. Fill the details of analysis setting as shown in Figure 4.9.

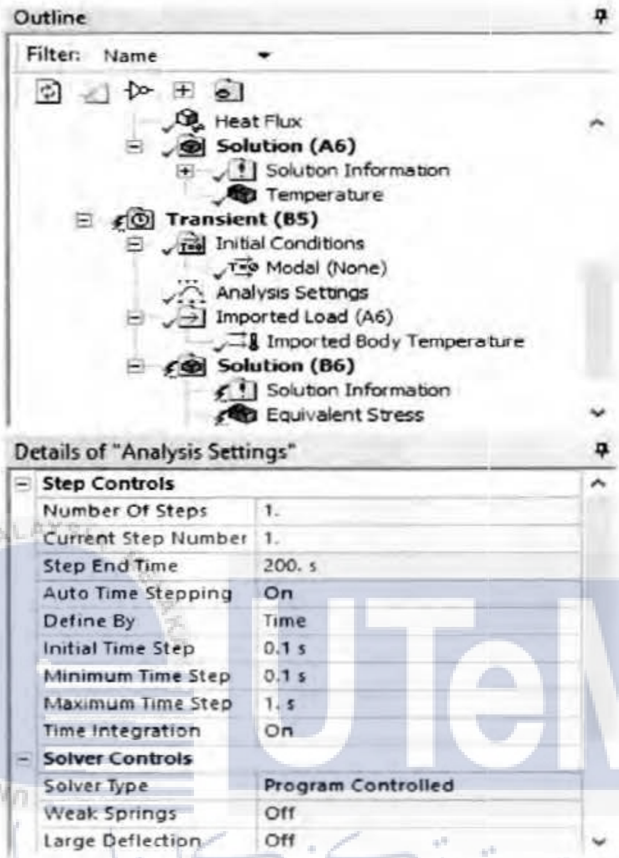


Figure 4.9: The Details of Analysis Settings of transient analysis

From the Figure 4.9, the details of analysis settings must be complete by fill the value of in steps control. The first one is the value of step end time that equal to 200 second based on the time that need to complete the cycle. Initial time and minimum time step change to 0.1 seconds. Next, fills the value of maximum time step equal to 1 second. The last one, change the weak spring and large deflection as "off" to complete the analysis setting.

IV. Complete the each of convection as shown in figure below

Figure 4.10: The heat convection on this brake rotor

From the Figure 4.10, the heat transfer coefficient was applied at the four places and assigned as shown in figure. The value of heat transfer coefficient of disc brake rotor can be refers from Table 4.3. The value of heat flux is equal to 0 because in this transient analysis, the heat flux assigned as tabular data. The next steps show how to complete the details of heat flux in this analysis.

V. The details of heat flux must be complete

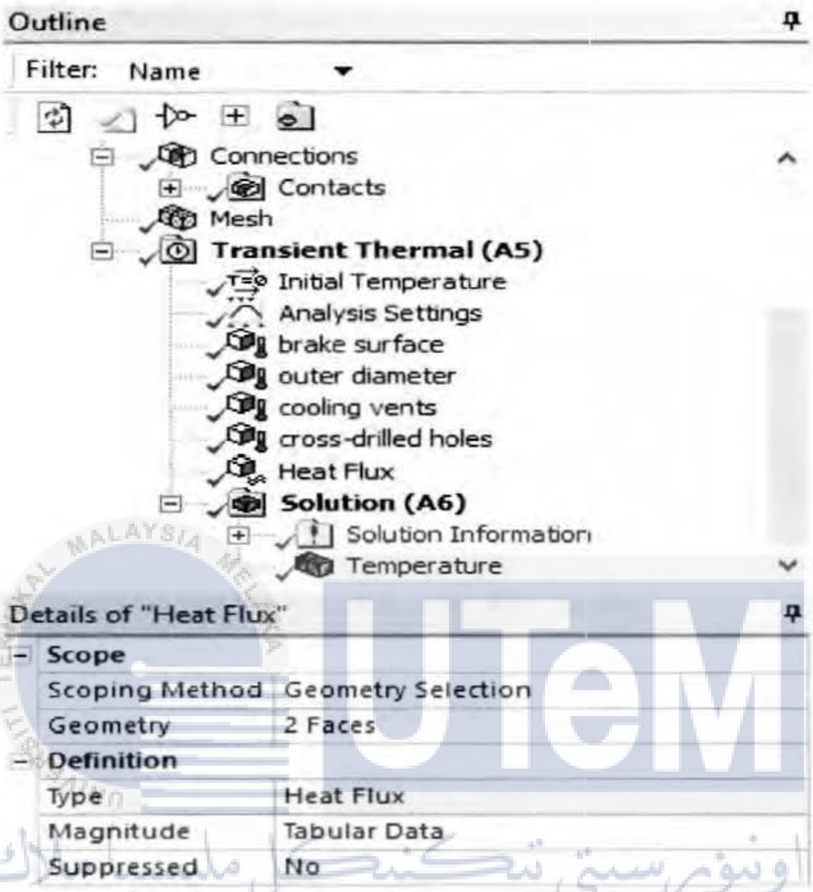


Figure 4.11: The details of heat flux in transient analysis

Based on Figure 4.11, the geometry of heat flux must be select first at the design. After that, the magnitude of heat flux is select as tabular data. That mean the magnitude of heat flux was put on the tabular data as shown in Table 4.4. The last one, the suppressed is select as "no".

VI. Complete the tabular data as shown in Table 4.4.

Table 4.4: The tabular data of transient analysis

Load	Braking	Heat Flux	
		Time (s)	**W/m^2**
1	Heating	0	1.7763×10^3
		2.85	1.7763×10^3
	Cooling	2.86	0
		20	0
2	Heating	20.1	1.7763×10^3
		22.85	1.7763×10^3
	Cooling	22.86	0
		40	0
3	Heating	40.1	1.7763×10^3
		42.85	1.7763×10^3
	Cooling	42.86	0
		60	0
4	Heating	60.1	1.7763×10^3
		62.85	1.7763×10^3
	Cooling	62.86	0
		80	0
5	Heating	80.1	1.7763×10^3
		82.85	1.7763×10^3
	Cooling	82.86	0
		100	0

6	Heating	100.1	1.7763×10^3
		102.85	1.7763×10^3
	Cooling	102.86	0
		120	0
7	Heating	120.1	1.7763×10^3
		122.85	1.7763×10^3
	Cooling	122.86	0
		140	0
8	Heating	140.1	1.7763×10^3
		142.85	1.7763×10^3
	Cooling	142.86	0
		160	0
9	Heating	160.1	1.7763×10^3
		162.85	1.7763×10^3
	Cooling	162.86	0
		180	0
10	Heating	180.1	1.7763×10^3
		182.85	1.7763×10^3
	Cooling	182.86	0
		200	0

From the table above, the value of cooling is equal to 0 for all cycle because it assumed as the brake pedal was released during cooling process. While the value of heat flux during the heating is equal to 1.7763×10^3 w/m^2. The time of 10 cycle to complete is equal to 200 second. The value of 2.85 second is the braking time applied on the disc brake rotor and its continue for the 10 cycle.

CHAPTER 5

RESULT AND DISCUSSION

5.1 Overview

In this chapter, the result for thermal stress analysis of steady-state and transient analysis has been show. As we know, the high temperature during the braking process can cause brake fade, premature wear and bearing failure. The excessive heat also can occur during braking process that will be affects the disc brake rotor. Non-uniform brake behavior can cause noise and roughness because of uneven distribution of heat in the disc brake rotor design. So, from the analysis the uneven distribution of heat and temperature can be detects in early stage before the design was fabricated. It also provides safety and efficiency during the braking process. The calculation of each nodal displacement to calculate stress and strain is required in thermal stress analysis. The result of both analyses is validated using the analytical calculation in order to determine the maximum temperature of disc brake rotor at each of the cycle repeated braking. Cycle of repeated braking was used in transient analysis to complete the Table 5.1. The value of braking system has been refers from Chapter 3.

5.2 Steady-State Analysis and Structural Analysis

5.2.1 Steady-State Thermal Analysis

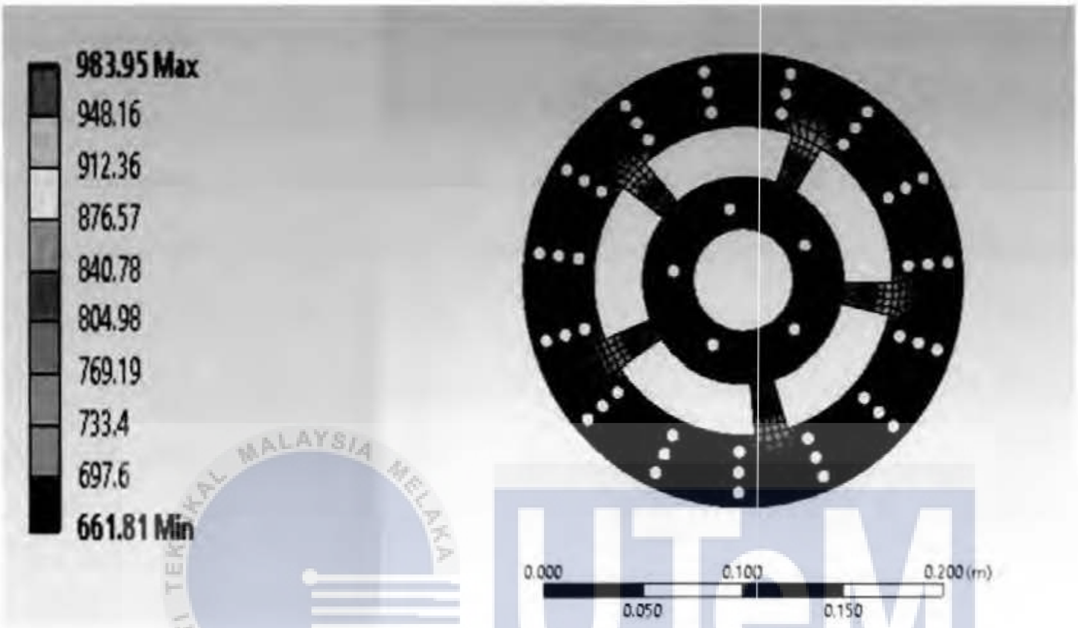


Figure 5.1: The temperature of Steady-State Thermal analysis

For the steady-state analysis, when the brake was applied on the disc brake rotor design it will produce heat. That is happen because the friction between the brake pads and disc rotor will produced heat on the disc brake rotor. As we can see from the Figure 5.1, the result show the minimum temperature value is 661.81 K while the maximum temperature value for disc brake rotor was 983.95 K. The minimum value of this design is when the Formula Varsity car is move without using brake. When the brake is applied, value of heat is increased because of the friction. Based on the steady-state analysis, the high temperature is detects at the outer surface which is the friction between brake pads and disc rotor.

The temperature slowly cools down when it transfer to the inner cooling vents. That mean, the heat transfer from the outer surface to the inner cooling vents and the heat dissipated to the air because of the cross-drilled holes. The service temperature based on Table 3.3 for the composite graphite iron is -160°C until 550°C. The value for the maximum temperature for composite graphite iron in kelvin is 823.15 K. Based on the steady-state analysis, the value of maximum temperature is 983.95 K which is exceed from the value of maximum temperature of composite graphite iron. That mean it exceed the melting point of composite graphite iron. It difficult to determine the result due to the high temperature recorded in steady-state analysis. In order to predict the temperature distribution on disc brake rotor, the transient analysis was applied.

5.2.2 Steady-State Structural Analysis

In this structural analysis, the results from the steady-state have been connected to this analysis. The results of this structural analysis have been divided into two parts. The first one is equivalent stress analysis and the others one is total deformation occur in disc brake rotor. Equivalent stress analysis result can be refers on Figure 5.2 while total deformation result can be refers on Figure 5.3.

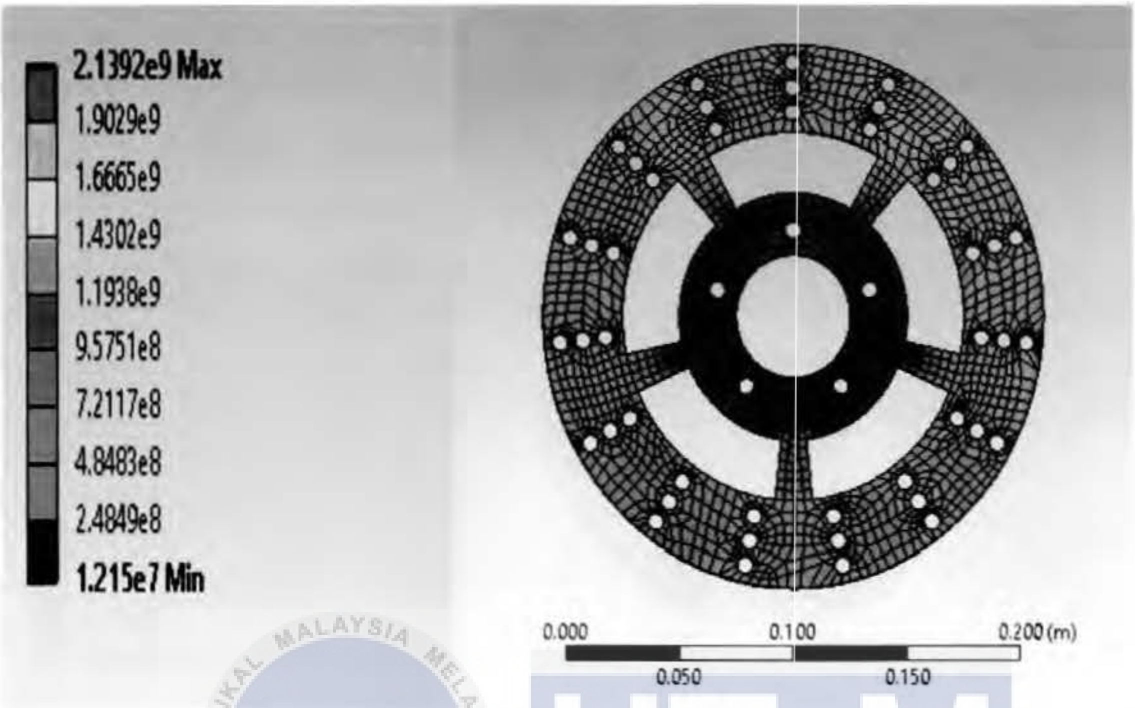


Figure 5.2: The equivalent stress of structural analysis on the disc brake

From Figure 5.2, it shows the equivalent stress of structural analysis on the disc brake rotor design. Obviously, the minimum stress is 0.95751 GPa because at middle of disc brake rotor their color was green. For the outer surface, the yellow color mean the value for maximum stress is from 1.1938 GPa until 1.9029 GPa. Based on Table 3.3, the value of yield strength for composite graphite iron is 415 MPa which is low than the maximum stress from the structural analysis. Due to the high stress in structural analysis from steady-state, it difficult to predict the stress behavior on disc brake rotor. Therefore, the transient analysis was applied to improve the result.

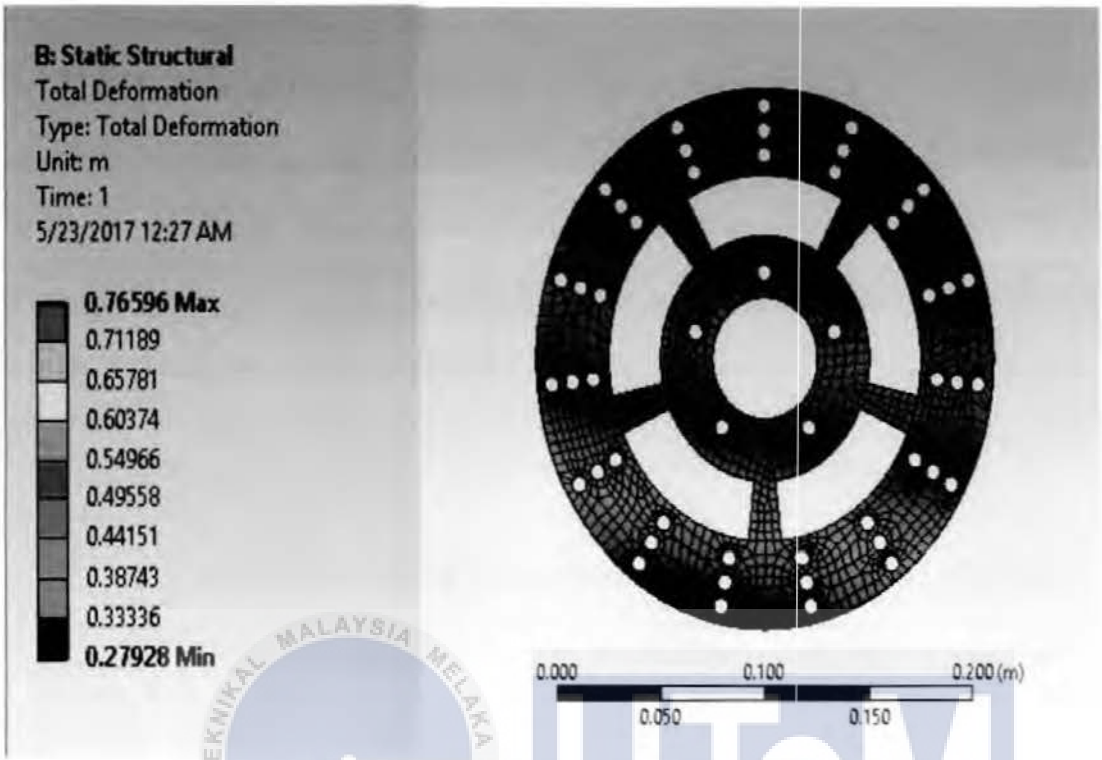


Figure 5.3: The total deformation in static structural analysis

From Figure 5.3, it shows the brake disc rotor has been through total deformation. An observation can be made by looking at the colour at the surface of disc brake rotor. The red colour means there are deformation highly occur at that place, while the blue represent there is minimum deformation. The lowest or minimum value of total deformation is 0.27928 Pa that occur at the above of disc brake rotor. The highest or maximum deformation recorded is 0.76596 Pa at the below of disc brake rotor. The others colour such as green and yellow represent the deformation going to change their form.

5.3 Transient Analysis

In this transient thermal analysis, 10 load cycles with total time 200 seconds are applied to investigate the cooling performance and thermal stress of disc brake rotor. Based on chapter 4.3 the braking times for formula varsity are 2.83 ≈ 2.85 second. Each cycle contain 20 second where 2.85 second of braking and 17.15 second of idle. The result of the analysis was tabulated as shown in Table 5.1.

Table 5.1: The cooling performances of formula varsity disc brake rotor

Cycle	Time (s)	Maximum Temperature (K)
0	0	303.15
1	2.85	329.09
	20	324.89
2	22.85	353.28
	40	342.85
3	42.85	367.09
	60	354.10
4	62.85	377.33
	80	360.36
5	82.85	385.16
	100	363.71
6	102.85	391.44
	120	379.98

7	122.85	406.51
	140	382.06
8	142.85	402.33
	160	391.40
9	162.85	414.86
	180	396.29
10	182.85	422.56
	200	390.94

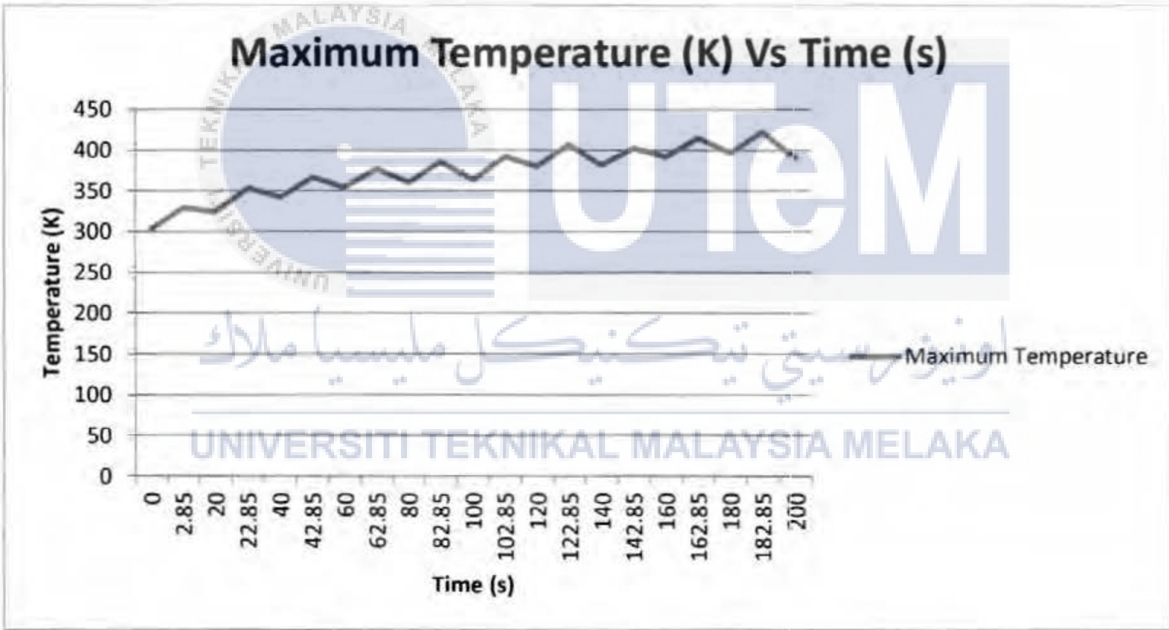


Figure 5.4: The graph of maximum temperature versus time

Next, the transient analysis result has their maximum and minimum value of temperature for 10 cycles. But only three cycles have been choose to compare and discuss the result. The cycle that has been chosen is 1st cycle, 5th cycle and 10th cycle.

5.3.1 Transient thermal at 1st cycle

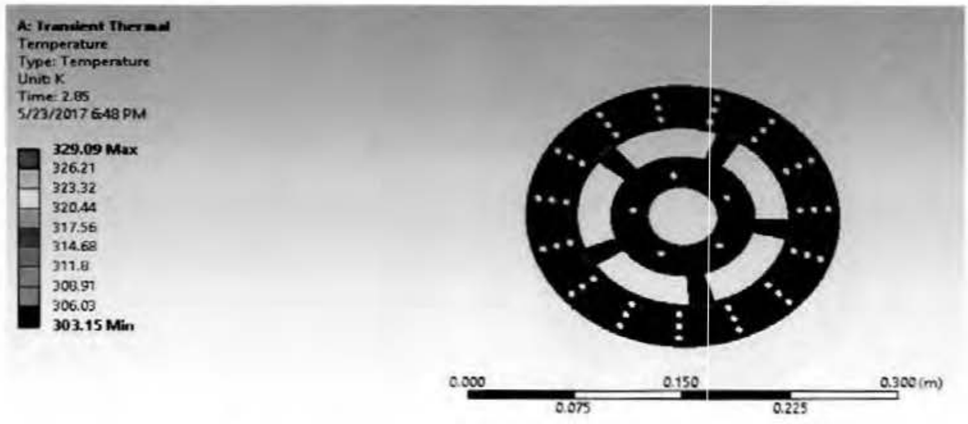


Figure 5.5: Temperature at 2.85 second

Figure 5.6: Temperature at 20 second

As we can see from the Figure 5.5 and 5.6, the temperature is different because the time taken for brake disc to cooling down from 2.85 second to 20 second. The value of maximum temperature at 2.85 seconds is 329.09 K and then it cooling down until 20 second. The value for maximum temperature recorded at 20 second equal to 324.89 K. From that, the analysis approve that the value of maximum temperature reduce or cooling down from 329.09 K to 324.89 K.

5.3.2 Transient thermal at 5^{th} cycle

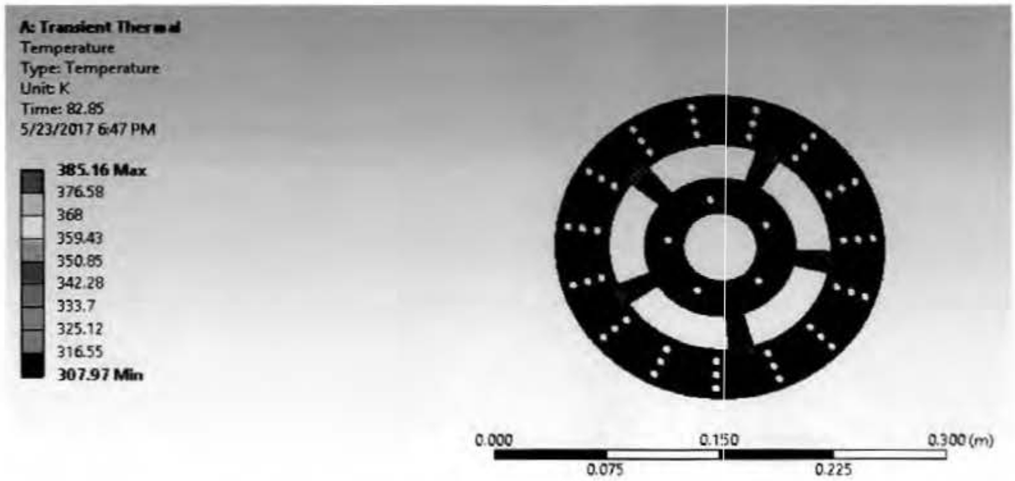


Figure 5.7: The result transient analysis temperature at 82.85 second

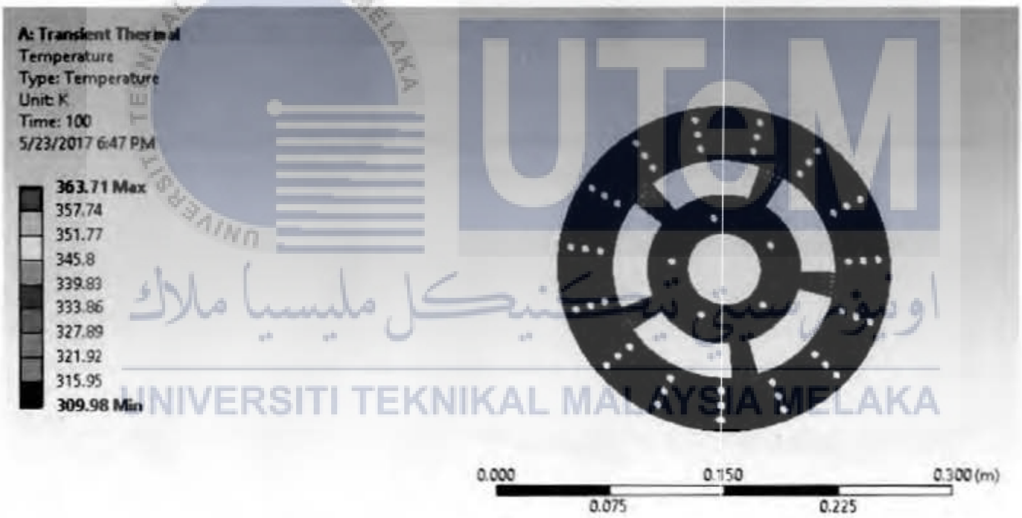


Figure 5.8: The result transient analysis temperature at 100 second

From the both figure above, the maximum value for each temperature was 385.16 K and 363.71 K. As we can see, the value of maximum temperature decrease from the 82.85 second to 100 second is 21.45 K. The cooling down of disc brake rotor can be seen in this analysis based on the temperature at the 5^{th} cycle.

5.3.3 Transient thermal at of 10th cycle

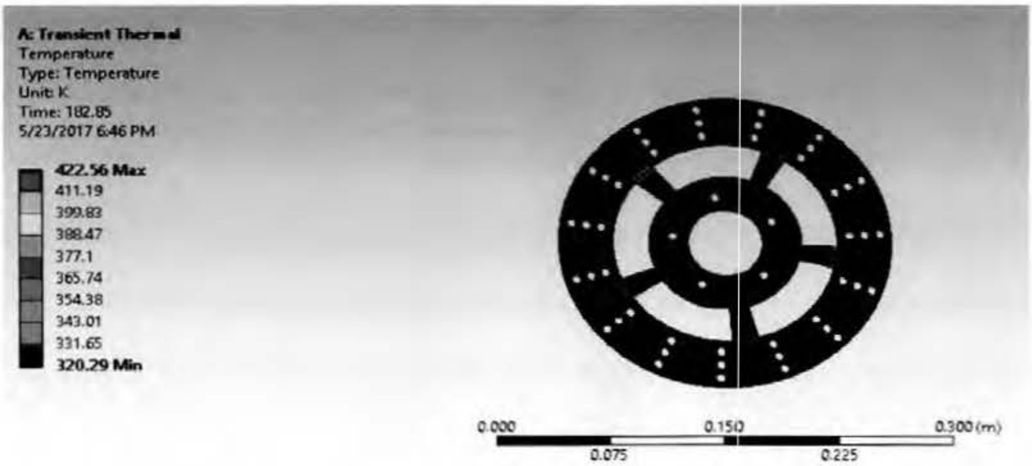


Figure 5.9: The result transient analysis temperature at 182.85 second

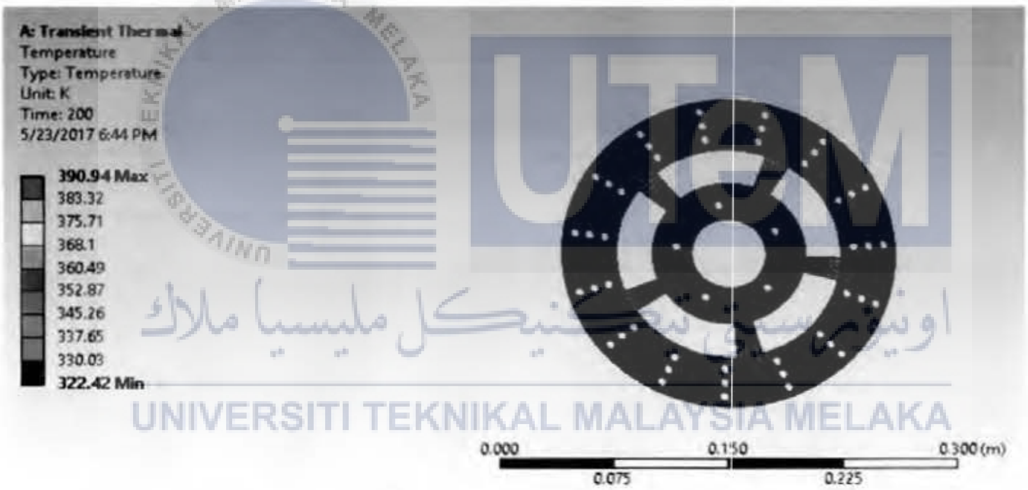


Figure 5.10: The result transient analysis temperature at 200 second

From the Figure 5.9 and 5.10, it shows the 10^{th} cycle of transient analysis which is the last of cycle. The value of maximum temperature also decrease same as others cycle. The maximum temperature for both 182.85 and 200 second is 422.56 K and 390.94 K. The amount of temperature decrease from 182.85 second to 200 second is 31.62 K.

As a conclusion for this transient analysis, the value of maximum temperature is decrease when it through the cooling process. When the brake was applied at certain time based on Table 5.4, the heating process is occur and the value of heat flux is $177.63 \times 10^3\ W/m^2$. The cooling process is occurring when the brake is released and the value for heat flux is $0\ W/m^2$. The maximum value recorded in this transient analysis is 422.56 K at the 10^{th} cycle which is it can be accepted because not exceed the value of composite graphite iron which is equal to 803.15 K. The actual temperature of disc brake rotor can be less or more due to limitation during the analysis. But, temperature for this analysis can be acceptable to use in formula varsity disc brake rotor based on transient analysis.

5.4 Transient Structural Analysis

5.4.1 Equivalent (Von-Mises) stress

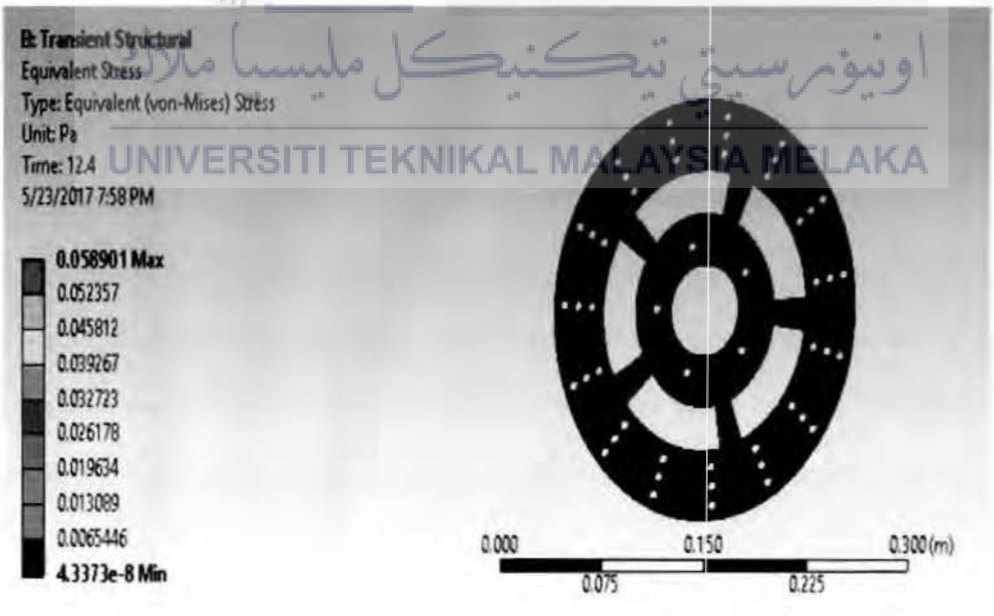


Figure 5.11: The maximum Von-Mises stress

Tabular Data

	Time [s]	Minimum [Pa]	Maximum [Pa]
2	0.2	7.0776e-008	3.3977e-002
3	0.5	7.5272e-008	2.0118e-002
4	1.4	5.6631e-008	2.3825e-002
5	2.4	1.1867e-007	2.1577e-002
6	3.4	1.1135e-007	2.1698e-002
7	4.4	8.6469e-008	1.8078e-002
8	5.4	2.0232e-007	2.3002e-002
9	6.4	1.4832e-007	2.6837e-002
10	7.4	7.1102e-008	2.9082e-002
11	8.4	6.4079e-008	3.3459e-002
12	9.4	3.5489e-008	2.3805e-002
13	10.4	7.1369e-008	2.3983e-002
14	11.4	6.8052e-008	2.8431e-002
15	12.4	4.3373e-008	5.8901e-002
16	13.4	1.2264e-007	2.0148e-002

Figure 5.12: Tabular data of Equivalent (Von-Mises) Stress

From the Figure 5.11, it shows the result highest equivalent stress on the disc brake rotor occurring at 12.4 second. The minimum value for equivalent stress is 4.337×10^{-8} Pa while the highest equivalent stress at 5.8901×10^{-2} Pa. The tabular data from Figure 5.12 show the time with the minimum and maximum value of stress occur at that time. The value for the Von-Mises is quite small because the temperature change on the transient analysis is not too high. The minimum temperature value is rom the transient analysis is 303.15 K while for the highest temperature is 422.56 K. So the different value of both temperature only 119.41°C. It can be conclude that the temperature affect the equivalent stress on this research.

5.4.2 Total Deformation

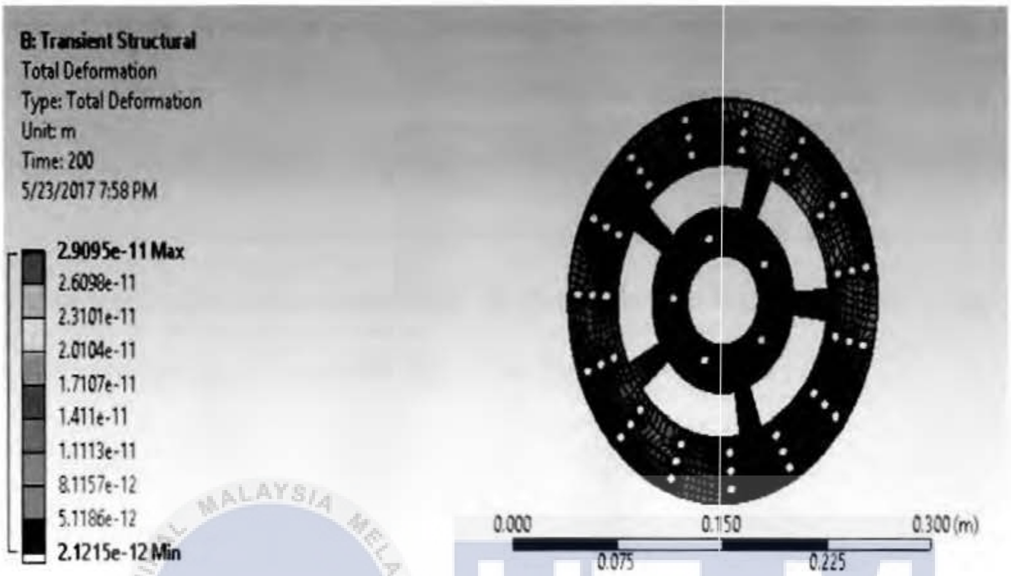


Figure 5.13: The total deformation occur in transient structural analysis

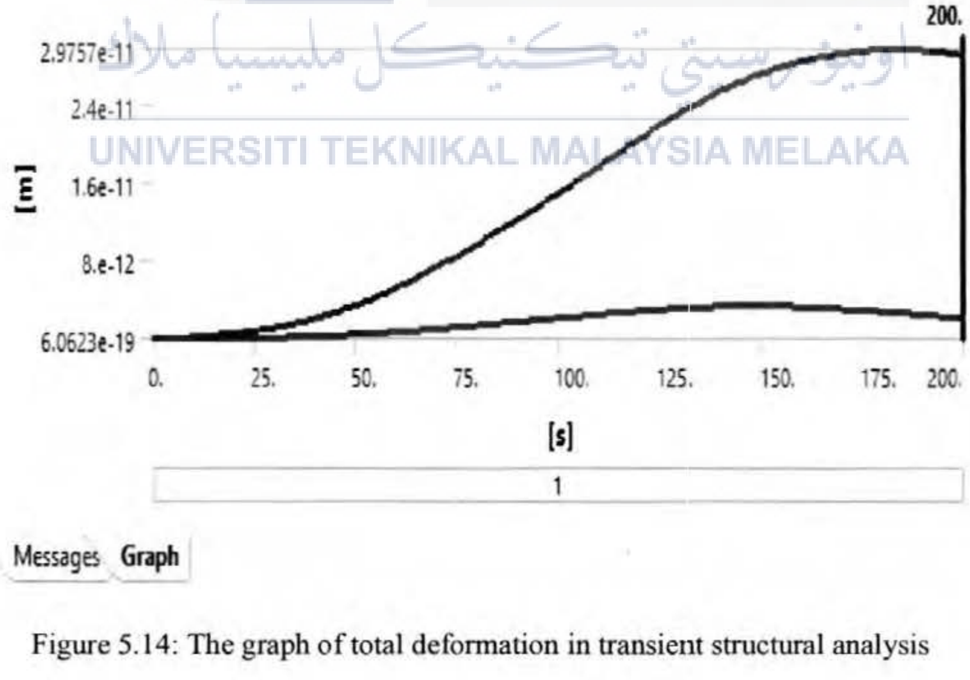


Figure 5.14: The graph of total deformation in transient structural analysis

The Figure 5.13 shows the result of total deformation in transient structural analysis. As we can see, the maximum deformations occur at the red region while the minimum deformations occur at blue region. The maximum and minimum value of deformation respectively is 2.9095×10^{-11} m and 2.1215×10^{-12} m. From the result simulation, it shows the deformation in this analysis occurs but the value is small. That mean, the deformation of disc brake rotor is small and maybe it will take long time to change their form. In conclusion, the value of total deformation is small thus the failure for this brake disc rotor is also small. The design expected can withstand the high stress based on the simulation.

5.5 Validation of Results

5.5.1 Introduction

The result from the steady-state and transient analysis can be validated through journal, analytical solution and information of formula varsity from the internet. The analytical solution has been used to validate the result by adapting the Eq. from the Limpert (1999). The temperature on disc brake rotor was assumed to be uniform and the both heat transfer coefficient and thermal properties is constant (Limpert, 1999). The comparison between the transient analysis and steady-state analysis was performed. From the result of simulation, the validation is applied on transient scheme.

5.5.2 Analytical Method

The lumped equation during the repeated braking adapted from Limpert (1999) was applied:

$$\frac{T(t) - T_i}{T_i - T_\infty} = e^{\frac{(-h_R A_R t)}{(\rho_R c_R v_R)}}$$

Where,

A_R = Rotor surface ($0.026358\ m^2$)

h_R = Heat transfer coefficient ($221.52\ W/m^2$K)

t = Cooling cycle time (200 second)

T_∞ = Ambient temperature, K

T = Temperature at time, K

ρ_R = rotor density (7100 kg/m^3)

c_R = Specific heat (475 j/kgK)

v_R = Rotor volume ($1.379 \times 10^{-4}\ m^3$)

The average temperature increase per stop is

$$\Delta T = \frac{P_{bo} t_s}{\rho_R C_R v_R}$$

$$= \frac{46750 \times 2.83}{7100 \times 475 \times (1.379 \times 10^{-4})}$$

$$= 284.5 \text{ K}$$

$$T_1 = 284.5 + 303.15$$

$$= 587.65 \text{ K}$$

The brake disc surface temperature after 2 cycles of braking application:

$$T_2 - T_\infty = \frac{\left[1 - e^{\frac{(-n_a h_R A_R t)}{(\rho_R c_R v_R)}}\right] [\Delta T]}{1 - e^{\frac{(-h_R A_R t)}{(\rho_R c_R v_R)}}}$$

$$T_2 - T_\infty = \frac{\left[1 - e^{\frac{(-2(221.52)(0.026358)(200))}{((7100)(475)(1.379 \times 10^{-4}))}}\right] [284.5]}{1 - e^{\frac{(-(221.52)(0.026358)(200))}{((7100)(475)(1.379 \times 10^{-4}))}}}$$

$$T_2 \quad = 307.59 + 303.15$$

$$T_2 \quad = 610.74 \text{ K}$$

Table 5.2: The temperature of disc brake surface

Cycle Braking	Analytical Temperature (K)	Analysis Temperature (K)
1^{st}	587.650	329.090
2^{nd}	610.740	353.280
3^{rd}	612.630	367.090
4^{th}	612.775	377.330
5^{th}	612.791	385.160
6^{th}	612.792	391.440
7^{th}	612.793	406.510
8^{th}	612.793	402.330
9^{th}	612.793	414.860
10th	612.793	422.560

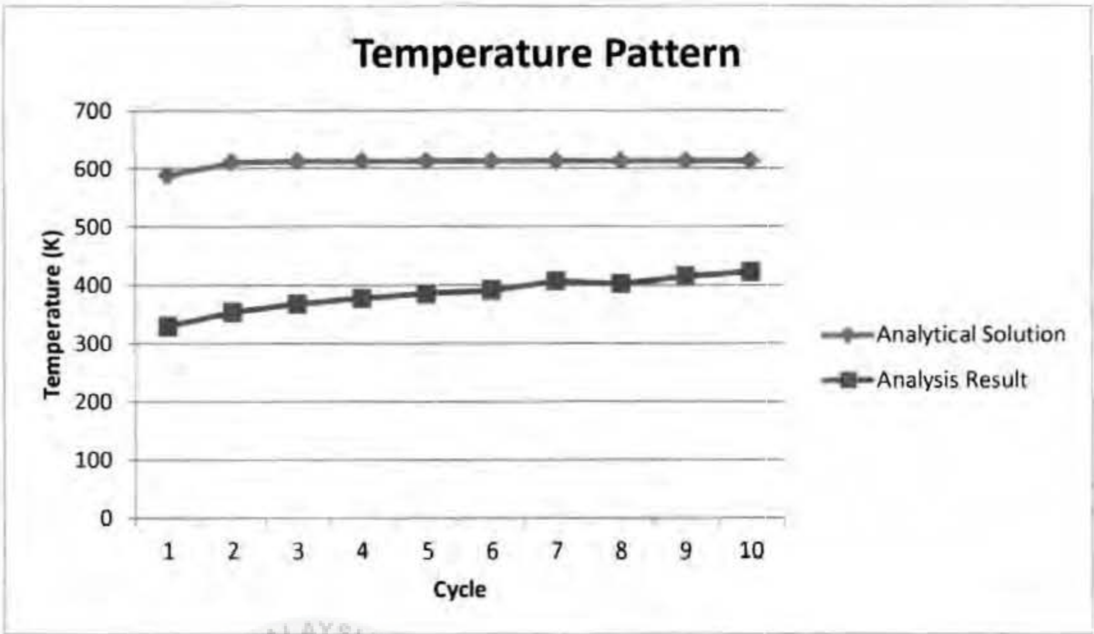


Figure 5.15: The maximum temperature between analytical solution and analysis result

Based on the result from Table 5.2, the maximum temperature of analysis result is equal to 422.56 K and the analytical solution is 612.793 K. From the result, the analytical solutions have higher temperature than the simulation in ANSYS. The difference between the maximum temperatures is bigger. The result of the analysis can be improved because the analytical solution more suitable for standard vehicle and maybe not for formula varsity disc brake rotor. So, the thermal stress analysis on formula varsity disc brake rotor has been successfully achieved based on the result.

CHAPTER 6

CONCLUSION

6.1 Overview

From this research of analysis, the thermal stress analysis contain of steady-state and transient analysis. The effect of temperature on disc brake rotor during braking process is must be considered. The accuracy of the result depends on the validity of the heat transfer coefficient at the surface of disc brake rotor. The temperature of disc brake rotor is increasing when the brake is applied and it slowly cool down when the brake pad was released. That mean, the heat dissipated through the convection process at the surface of disc brake rotor. The heat flux can influence or lead to brakes fade, thermal crack and other due to excessive thermal stress. The thermal stress analysis also reveals the behavior of disc brake during the braking process. From the simulation result, the material of composite graphite iron is suitable to use in this research because the maximum temperature of the simulation not exceed the maximum temperature of material. The equivalent (Von-Mises) stress value from the simulation also low than the material yield strength. So, it can be conclude that the composite graphite iron can withstand the heat generated and high stress during the braking process. The suitable material for this research is composite graphite iron along with the design can be acceptable.

6.2 Recommendation

Overall in this research, most of the objective has been achieved. The result simulation can be improved by using the analytical solution Eq. from the formula varsity car instead of using Eq. that more suitable for standard car. The ANSYS software also have their own limitations because it the student version. The limitation that I mean is the range of nodes and element is small compare to the full version. Therefore, for future work, I would recommend using full version ANSYS software so that the result is more accurate and acceptable. Lastly, I would like to suggest for analyze the effect of formula varsity on disc brake rotor using different parameter beside various design of brake disc rotor.

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