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Comparative analysis of Disc brake rotors using FEA

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Abstract*— One of the most critical systems in an automobile is the braking system. During braking the K.E and P.E of a moving vehicle is converted to thermal energy in the form of frictional heat in the brake disc and pads, this heat needs to be effectively transferred to ensure safe operation. The object of this study is to investigate the temperature variation and thermal flux distribution over a brake disc rotor during heavy braking (100 to 0 kph) using FEA. The disc brake is modelled using CATIA and analysis is done using ANSYS workbench. Thermal analysis of Models of four different types of brake rotors is done in the study and results are compared. The rotor types used are:

- ***A. Plane rotor***
- ***B. Drilled rotor***
- ***C. Slotted rotor***
- ***D. Ventilated rotor***

Keywords - Disc brake, Brake pad, Frictional heat, CATIA, ANSYS, FEA (Finite element Analysis), Thermal analysis.

I. INTRODUCTION

Automotive brake systems are used to regulate the speed of a vehicle by creating frictional force against the direction of motion. The brakes absorb kinetic energy and dissipate it as heat energy. A disk brake consists of a Rotor, which is driven by the wheel hub and a stationary housing called caliper. The caliper consists of Brake pads, a piston and hydraulic system as shown in fig 1.

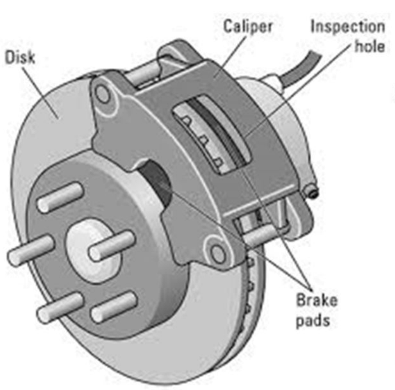

Fig 1

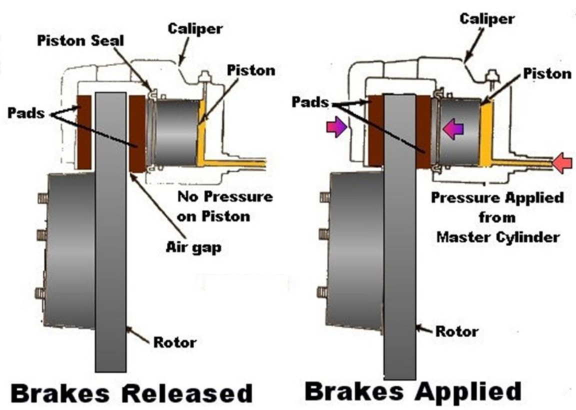

Fig 2

When the brake is applied, hydraulically actuated pistons move the brake pad into contact with the rotating rotor, the excess force generated by the fluid pulls the caliper frame. Due to the friction in between disk and pad surfaces, the kinetic energy of the rotating wheel is converted into heat and the speed gets regulated as in fig 2.

A. *Braking performance*

How well a brake system handles heat is affected by how much heat the rotors can absorb and how quickly they dissipate the heat that they absorb. The more the mass of the rotor, the more heat they can absorb. Also, the better the airflow over and through the rotor, the more effectively the rotor can transfer that heat to the ambient air flowing over it.

B. *Cooling of brakes and brake fade*

Cooling of the brake is very important as excess heat will reduce the friction between the contact surfaces and hence reduce braking efficiency, this phenomenon is called brake fade. Moreover, the temperature produced during braking should be less than the safe operating temperature of the material. In this study, different brake disc designs are analysed and compared based on the temperature variation and total heat flux plots obtained.

Upon first application of the brakes, the temperature rise is very rapid and increase as long as the brakes are applied while the wheels are turning. When the brakes are released, the temperatures spread out and start to drop. They drop faster if the car is still moving since there is more air flowing over the rotors, but they don't completely cool down that rapidly. If the car is driven hard and if there is a lot of braking the rotors never cool off, and each subsequent braking event adds more heat to the rotor before it can dissipate it. This is where rotor size and thermal capacity help.

C. Rotor mass and thermal capacity

The rotor must have enough mass to absorb all that heat because otherwise it could exceed the thermal capacity of the rotors to act as heatsinks. When that happens the rotors cannot dissipate the heat as fast as it is added into the rotors and since any given material of a particular mass has a specific thermal capacity, at this point the rotor cannot efficiently absorb the heat anymore and the brake rotor and pad temperatures will rise very rapidly and high enough to easily exceed the MOT (maximum operating temp) of the brake pads and may cause pad fade. It may also get so hot that it boils the brake fluid in the calipers and may even warp the rotor. A warped rotor can be identified b noticing changes in color. A bluish boundary will be visible somewhere between the rotor and hat as the heat at that point changes the molecular structure of the material.

D. Thermal stress and cracking

When the rotor is running close to the edge of its thermal capacity, weak spots like cross-drilled holes or slots on the rotor causes stress risers, coupled with the thermal expansion that occurs during braking and repeated hard use. The holes make it much easier to develop deep stress cracks in the rotors eventually forming a fragged rotor.

1) Brake rotor: The rotor is a rotating member that is attached to the wheel hub and rotates at the same speed as the wheels. When brakes are applied the piston presses the pads against the rotor. Various kinds of brake rotor designs are available today, but generally they can be grouped into four basic types as discussed.

2) Plane rotor: These are just plane discs, the contact surface is plane and has no holes or slots. It is the most commonly used rotor type for day to day running. It's very simple in construction and less costly. In comparison with other types of rotors, plane discs are stronger but not much efficient in cooling. But still, it is the best value for money among the four.

3) Drilled rotor: The friction surface of this rotor has cross drilled holes. The holes were introduced to address many issues. It serves as passage for gases and dust produced during heavy braking and it helps remove water if the rotor gets wet. In a plane disc the water may reduce the friction between the pads and the rotor, also if steam is formed it may act as a gaseous layer reducing friction further. Holes are also said to help in cooling but this is not at all significant because the holes are axial and there is very less airflow in this direction. There are a lot of problems too, cross drilled rotors have less surface area of contact between pad and brake, they have less mass and hence less capacity to absorb heat. When it is running close to the edge of the thermal capacity, cross-drilled holes become stress risers on the rotors. The holes make it much easier to develop deep stress cracks in the rotors. Race teams do not prefer cross-drilled rotors, they use either plain or slotted rotors. The cross-drilling reduces the thermal capacity and weakens the rotor courting the possibility of failure.

4) Slotted rotor: Slotted brake rotors have slots carved into the flat rotor surface. Unlike in case of plane rotors, the gases and dust produced during braking escape through the slots. The slots wipe against the brake pads when braking and keeps them clean but the pads tend to wear out faster when using a slotted rotor. Thus they are mostly used for race applications.

5) Vented rotor: A vented rotor consists of two brake rotors that are separated by vanes or projections in between. They make use of the increased surface area and airflow to dissipate heat very effectively, and directionally vented rotors are even more effective. A vented rotor acts in a similar fashion to an impeller wheel like in a turbo pump. The spinning action forces air outwards from the center and it induces airflow through the rotor with cold air being sucked in at the center and the hot air being flung out the edges. Vented rotors dissipate heat much better than non-vented rotors and directionally vented rotors improve the effectiveness. A downside to this is the resulting radiant heat, the rotor will actually heat everything surrounding it.

E. Brake pad

Brake pads are placed in the brake caliper with the friction surfaces facing the rotor. During braking the pistons squeeze the pads against the rotor and thus converts K.E into heat. Almost 20% of the heat produced is transferred to the pad and the caliper assembly

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and the rest goes to the rotor.

Assumption made for the study are

The vehicle is assumed to be travelling at 100kph and is brought to a standstill on braking (0 kph).

II. LITERATURE REVIEW

This literature is based on the study of four different types of brake disc rotors under similar loading conditions to compare the temperature distribution and cooling efficiency of each individual rotor. The brake rotors are made of Carbon ceramic composite. The maximum operating temperature of carbon ceramic discs used in passenger vehicles is in the range 350 - 450 ^{o}C, after that the rotor is prone to brake fade [2]. To enable easy dissipation of generated heat, the rotor must have sufficient thermal mass and proper surface area for efficient air cooling [3]. Material selection is done by considering many factors like vehicle load, compressive strength, heat dissipation rate, wear rate, cost of manufacturing and operation [7].

III. CALCULATIONS

In order to compare the four brake discs, the following parameters are kept same for all:

A. Applied Force on disc
B. Diameter and area of contact
C. Brake pad dimensions and area
D. Coefficient of friction between pad and rotor
E. Material of disc – (Carbon Ceramic composite)

Diameter of Disc Brake Rotor = 240 mm.
Rotor disc material = Carbon Ceramic Composite
Pad brake area = 2000 mm^2
Pad brake material = Asbestos
Coefficient of friction (Dry) = 0.3-0.5
Maximum temperature[2] = 350 ºC
Maximum pressure = 4MPa

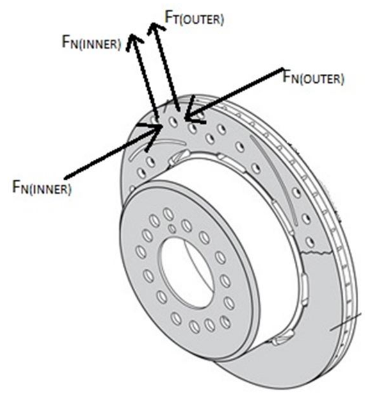

Fig 3

[2] Normal force between pad and rotor, $F_N = (P_{MAX} / 2) \times$ A pad brake area
Coefficient of friction, $\mu = 0.5$
Tangential force between pad and rotor (Inner face),
$F_{T(INNER)} = \mu \cdot F_N = (0.5)\,(0.5)\,(4\times10^6\ N/m^2) / (2000\times10^6\ m^2) = 2000$ N.
Tangential force between pad and rotor (outer face), $F_{T(OUTER)}$ is equal to $F_{T(INNER)}$ because same normal force and same material.
Total normal forces on disc brake, $F_T = F_{T(INNER)} + F_{T(OUTER)} = 4000$ N

Brake Torque (T_B)- (Assuming that equal coefficients of friction and normal forces F_N on the inner and outer faces)

Brake torque, $T_B = F_T . R$, where, μ = coefficient of friction

. R = Radius of rotor disc

$T_B = (4000)\ (120\times10^{-3}) = 480$Nm

Heat generated Q= m . Cp . ΔT , where m = Mass of disc

Specific Heat Capacity, Cp = 800 J/kg °C

Developed Temperature difference ΔT = 100 °C

Q = m x 800 x 100

Area of generation of heat on disk (Area of contact) = $2\pi\ (R_1^2 - R_2^2) = 2\pi\ (0.110^{\,2} - 0.80^2) = 0.03573\ m^2$

Heat Flux = Heat Generated /area /second

$q = (Q_{DISC} / 0.0358) / 20\ (kW/m^2)$

The values of flux obtained after calculation for the four rotors are tabulated in Table I:

TABLE I: MASS AND HEAT FLUX FOR DIFFERENT ROTORS

Disc Type	Mass (kg)	Flux (kW/m^2)
Plane	0.5635	61.500
Drilled	0.5289	58.994
Slotted	0.5735	64.022
Vented	0.6371	71.173

IV. MODELLING OF ROTORS AND BRAKE PAD

All the four rotors and the brake pad were modelled in CATIA V5. The front brake rotors for most low-end sedans with a mass of 1500 kg is in the range 240-280mm. Also the thickness is taken in proportion. In the drilled and slotted rotors, the cross drill pattern and slot pattern on the discs are of the most basic kind. In the vented rotor, straight vanes are used with appropriate height.

A. Dimensions of brake disc used for study

All the four types of brake rotors used for this study are of similar dimensions and have the same hub design to make a fair comparison. The dimensions used for modelling the rotors are given in Table II.

TABLE II: DIMENSIONS OF BRAKE ROTOR

Diameter	Outer	Inner
Disc	240 mm	120mm
Hub	120 mm	60mm
Thickness	Rotor – 6mm	Hub -4mm

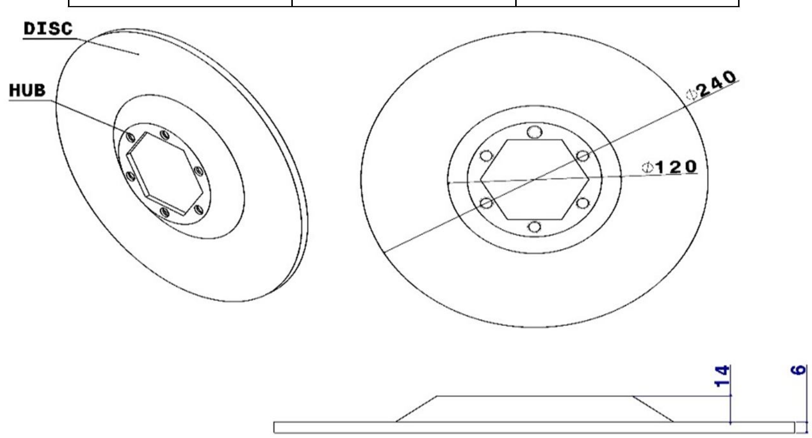

Fig 4: Basic rotor dimensions

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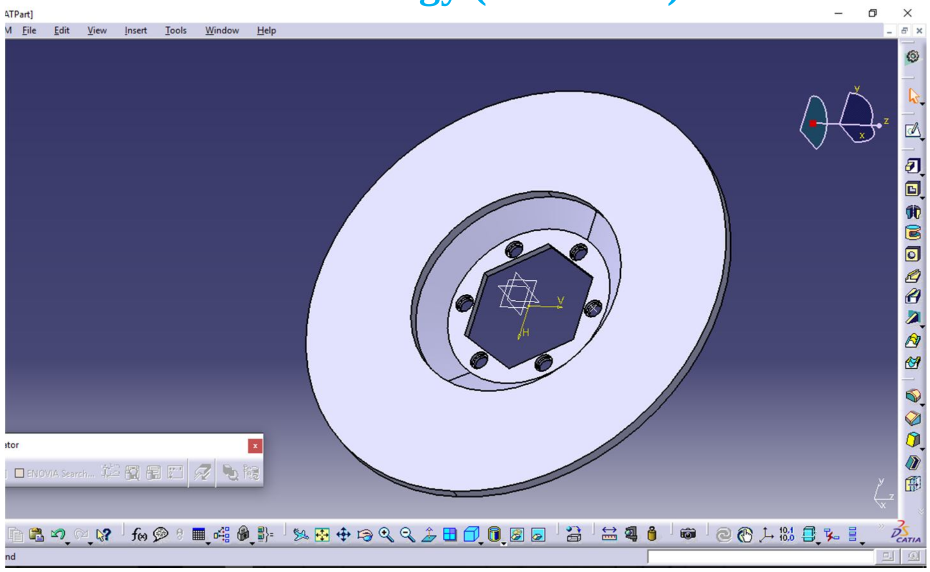

Fig 5: Plane rotor CATIA model

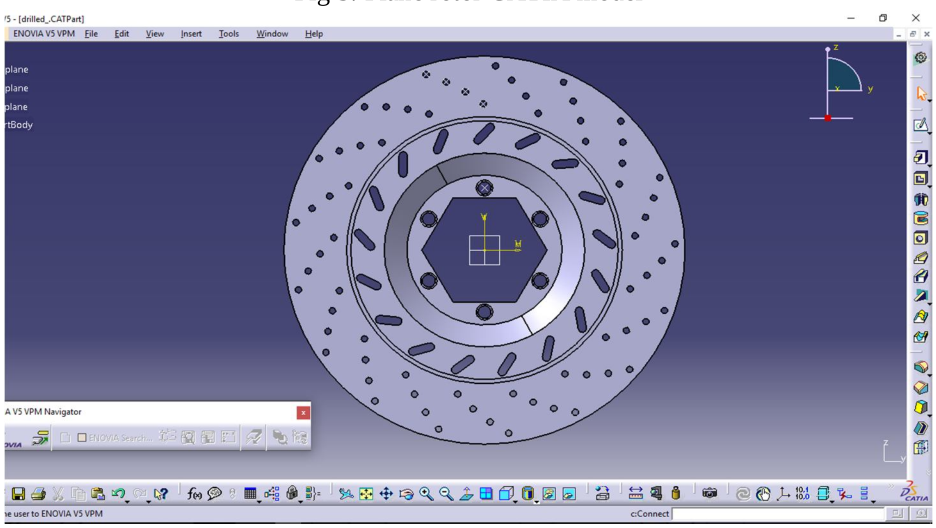

Fig 6: Drilled rotor CATIA model

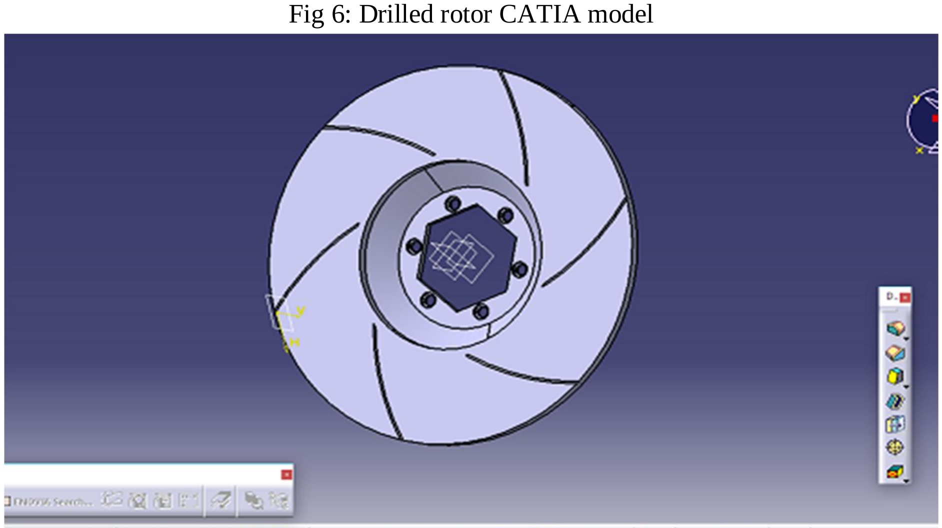

Fig 7: Slotted rotor CATIA model

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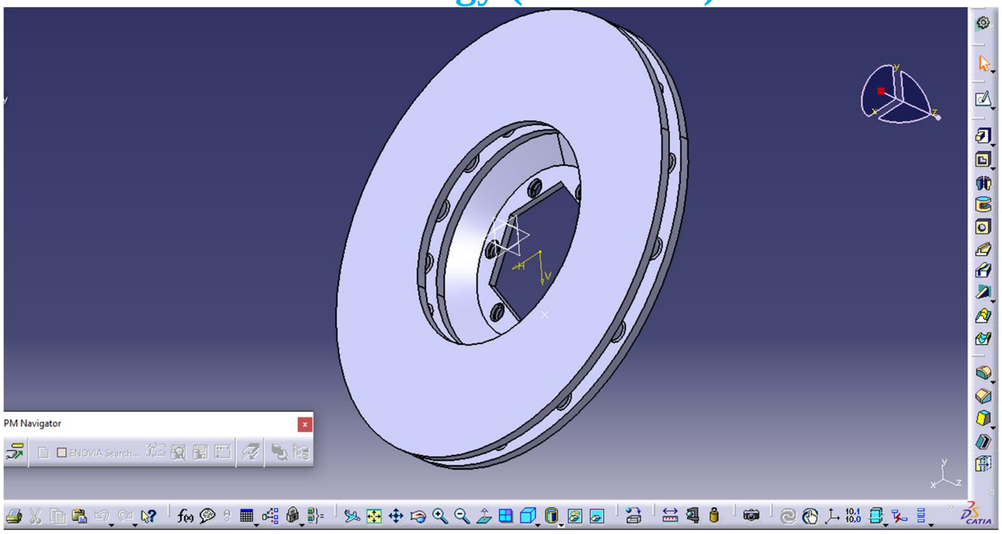

Fig 8: Vented rotor CATIA model

B. Brake pad used for study

The same brake pad is used for the analysis of all the four brake rotors; [5] dimensions of the brake pad are shown in the figure 9.

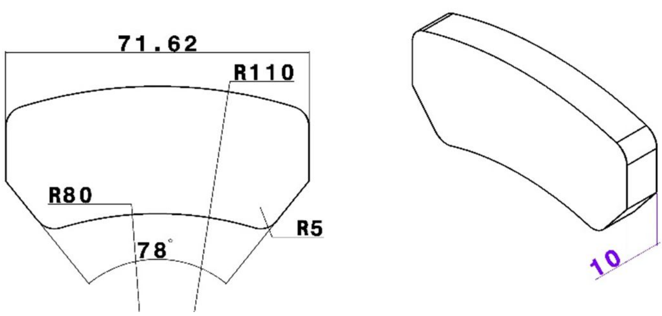

Fig 9: Brake pad dimensions

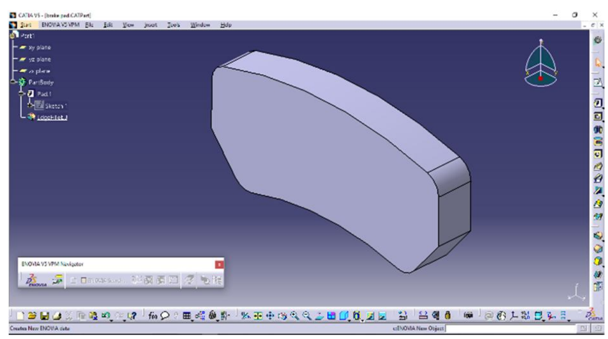

Fig 10: CATIA model of brake pad

V. THERMAL ANALYSIS OF ROTORS USING FEM (ANSYS SOFTWARE)

The Steady state thermal analysis of the brake discs was done in Ansys Workbench v14.5. Ansys makes use of FEM (Finite element method) to estimate the results of a problem based on the applied loads, boundary conditions and material properties which are *provided as inputs. The results can also be simulated. The following are the steps carried out during the analysis: -*

A. The material properties of carbon ceramic composite[4] are added to the project library: (Table III)

TABLE III: MATERIAL PROPERTIES

Property	Carbon Ceramic	Unit
Density	2450	Kg/m^3
Young’s modulus	250	GPa
Poisson ratio	0.32	
Ultimate Tensile Strength	185	MPa
Ultimate Compressive Strength	3000	Mpa
Thermal Conductivity	40	W/mK
Specific Heat	800	J/kgK
Coefficient of Thermal expansion	2.8	C^{-1}

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1) The CATIA model was imported into Ansys workbench Design modeler.
2) Mesh generation - auto mesh sizing of fine mesh is selected.
3) Heat flux(q) is applied on the region of contact of the pads and the disc during braking. The values of flux are given in TableI.
4) Radiation heat transfer at ambient temperature applied on outer surface area

B. Analysis of Plane disc

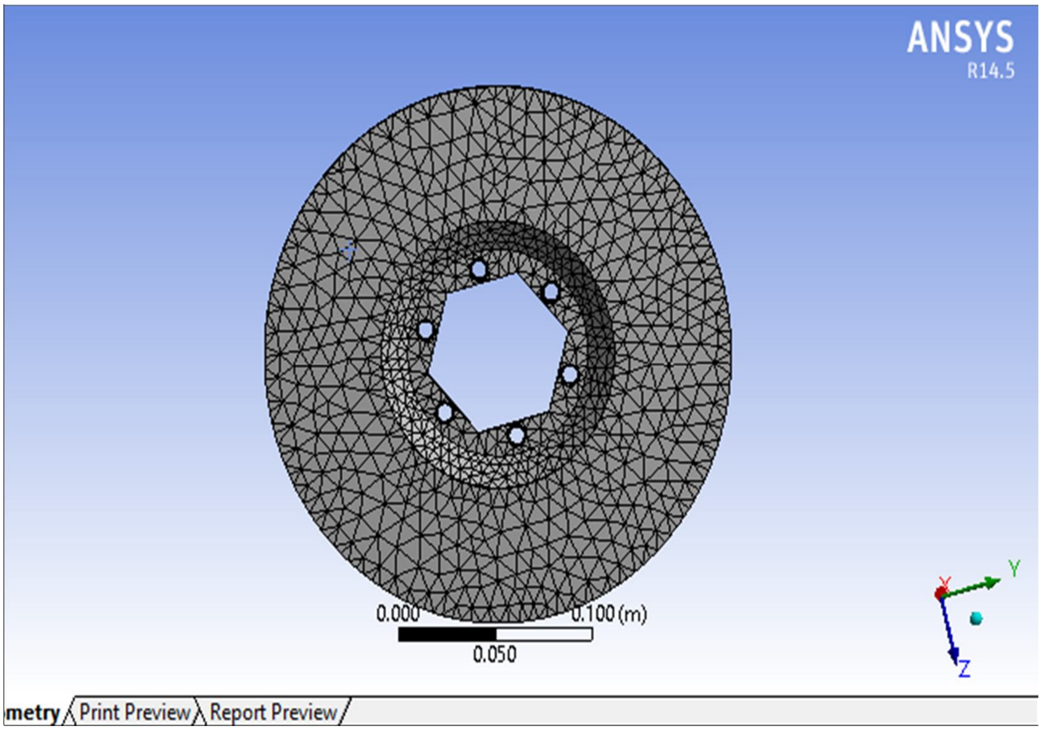

Fig 11: Mesh generation

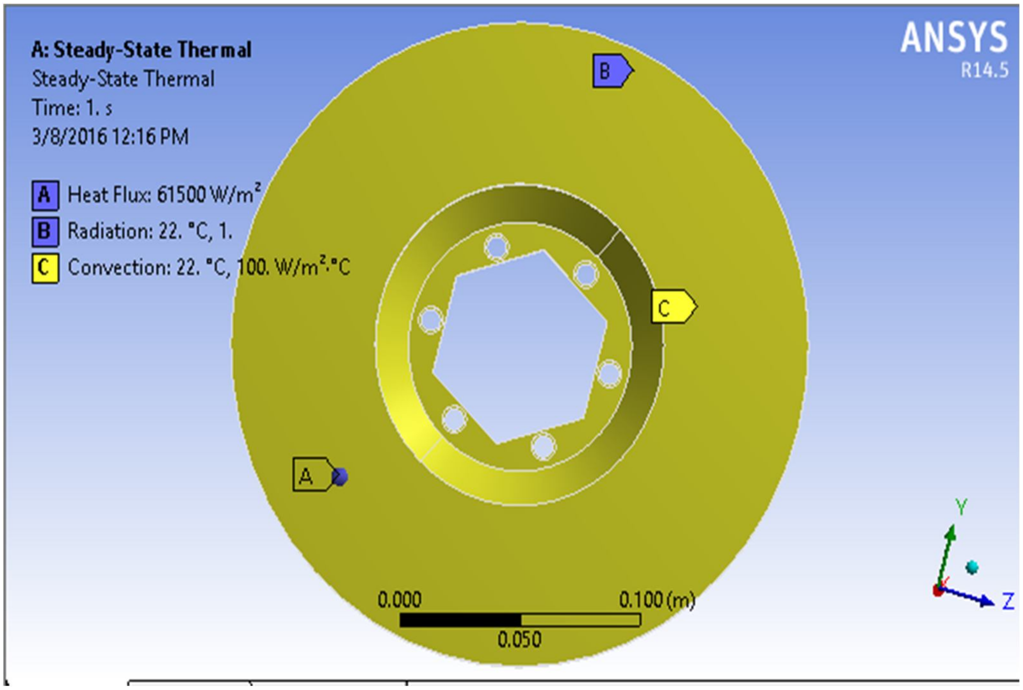

Fig 12: Applied thermal loads

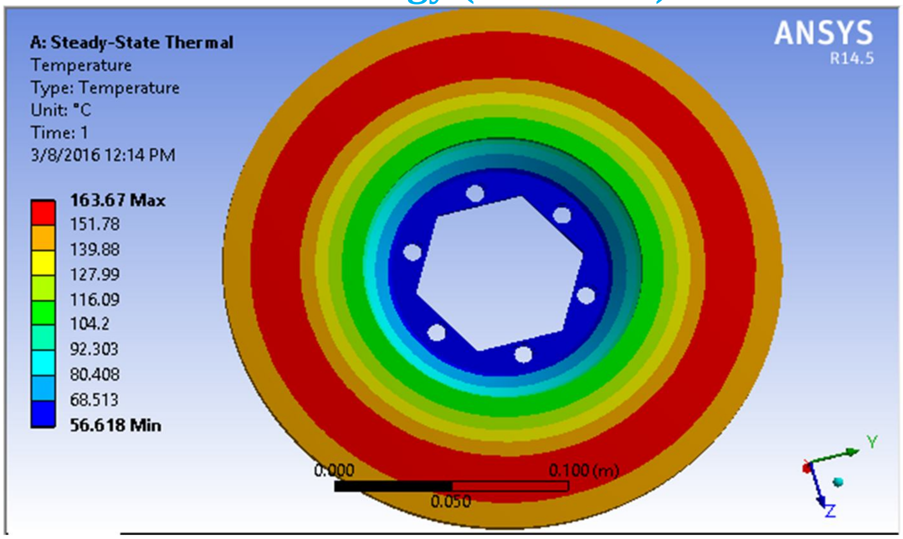

Fig 13: Obtained temperature distribution

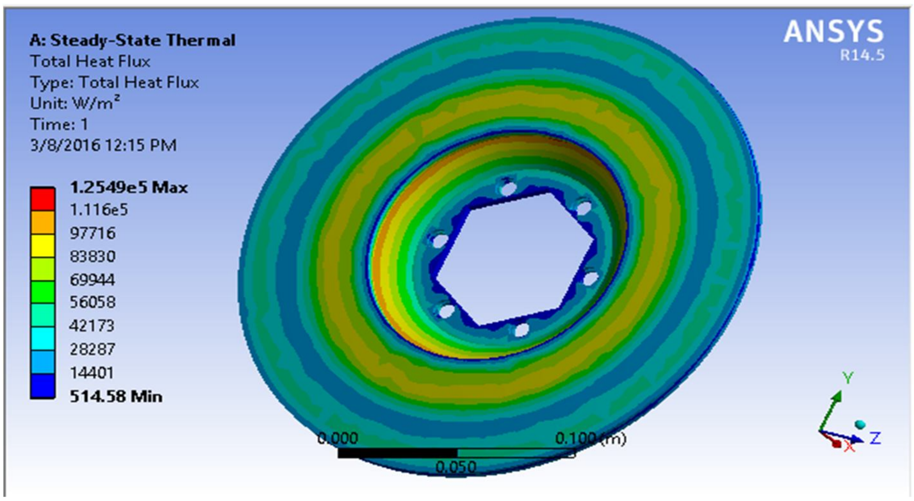

Fig 14: Total heat flux

B. Analysis of Drilled disc

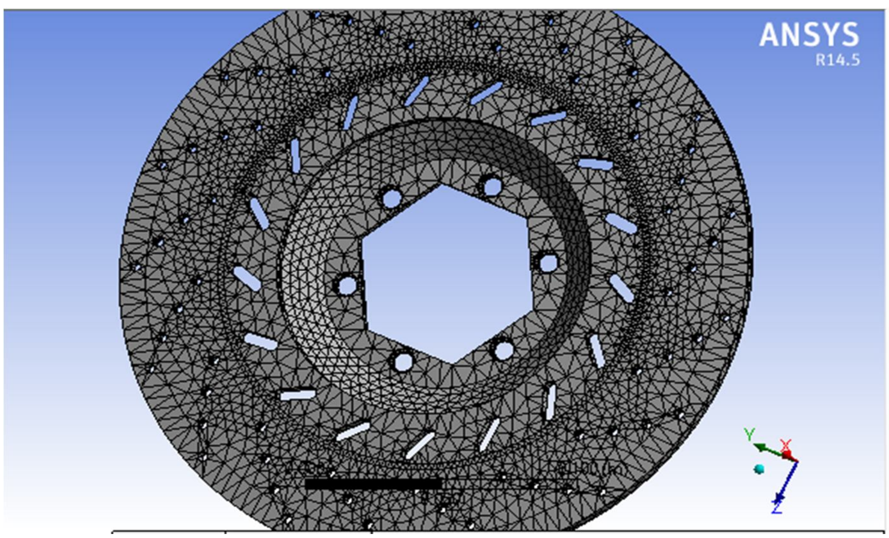

Fig 15: Mesh generation

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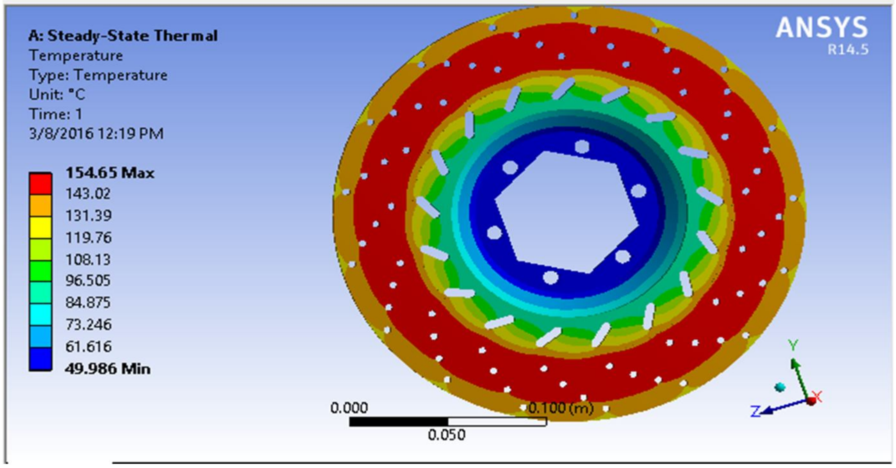

Fig 16: Temperature distribution

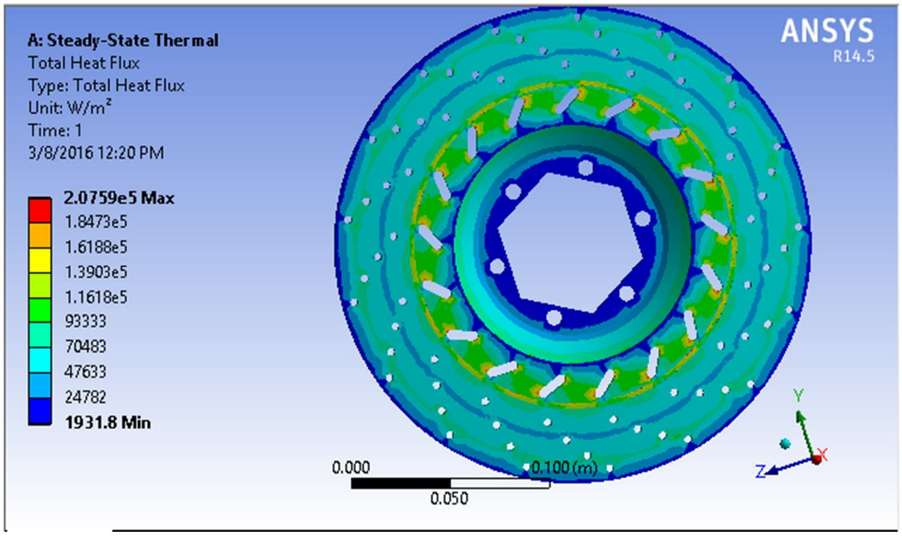

Fig 17: Total heat flux

C. Analysis of Slotted disc

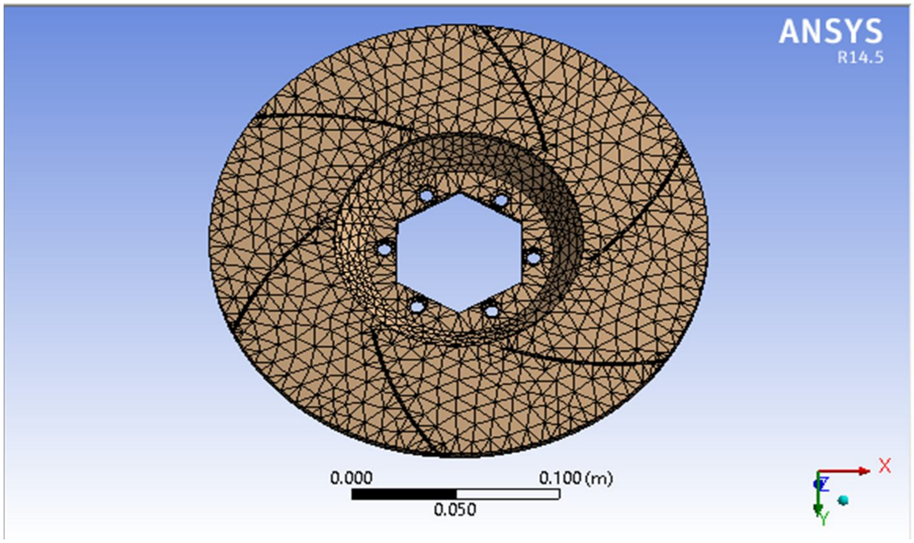

Fig 18: Mesh generation

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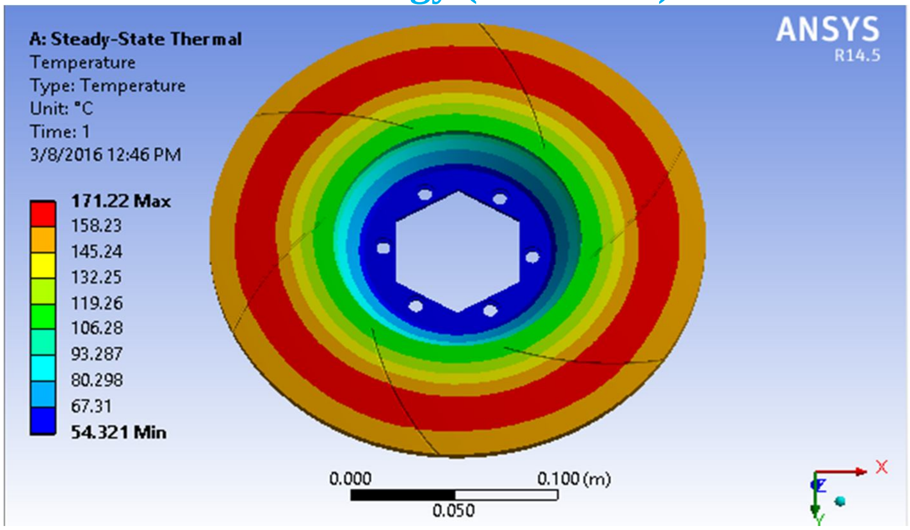

Fig 19: Temperature distribution

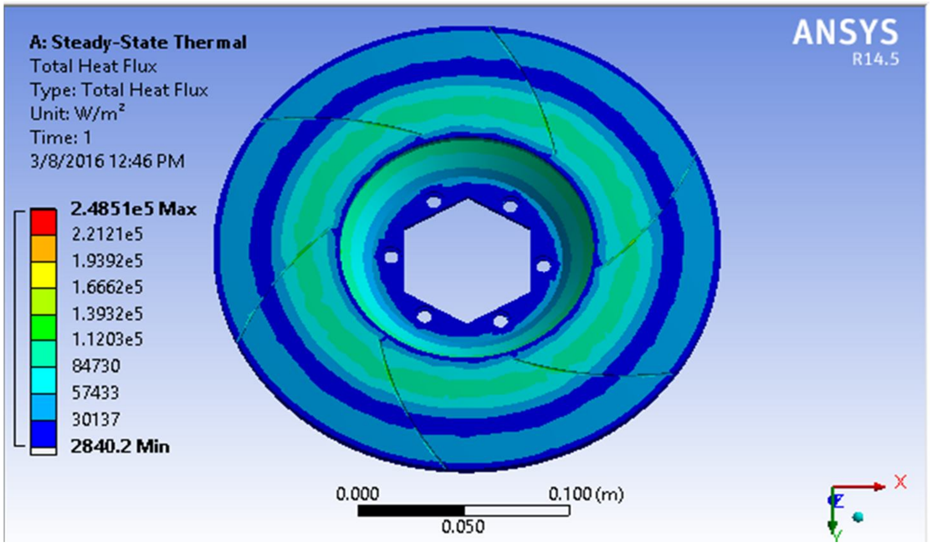

Fig 20: Total heat flux

D. Analysis of Vented rotor

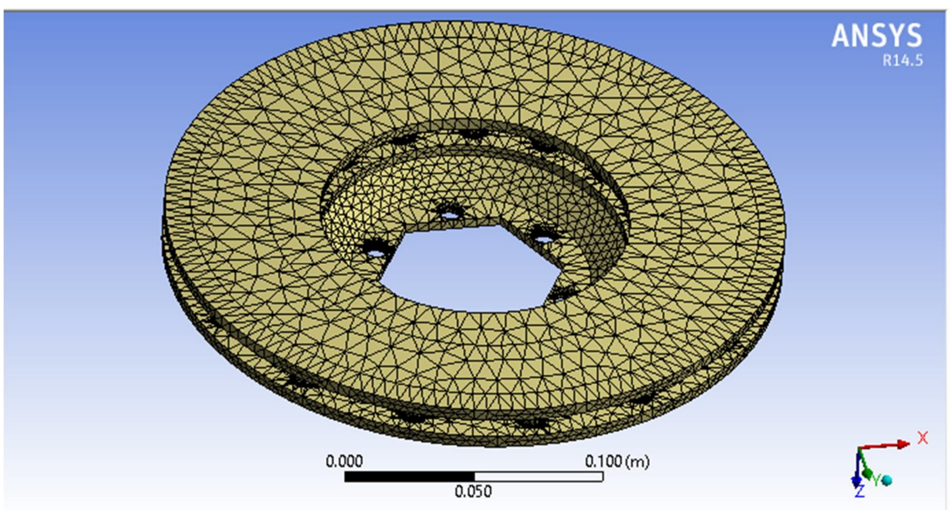

Fig 21: Mesh generation

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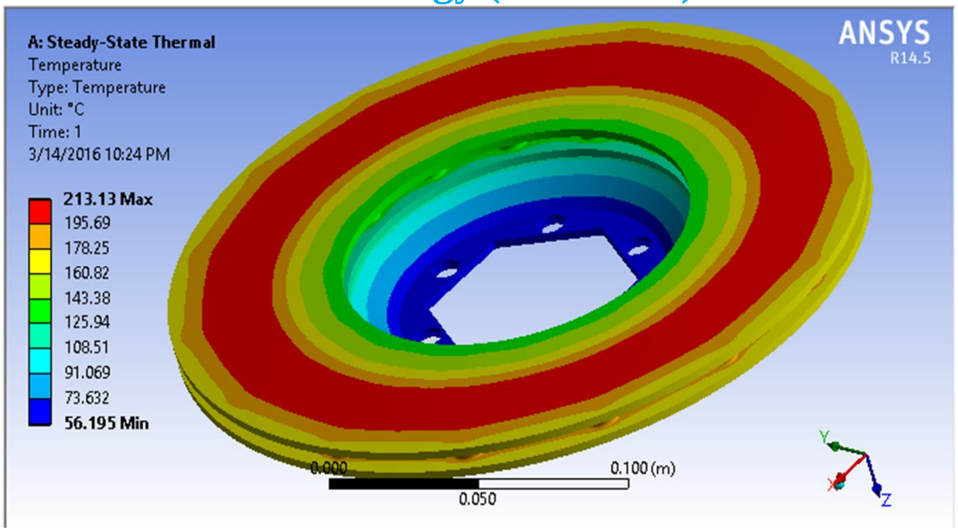

Fig 22: Temperature distribution

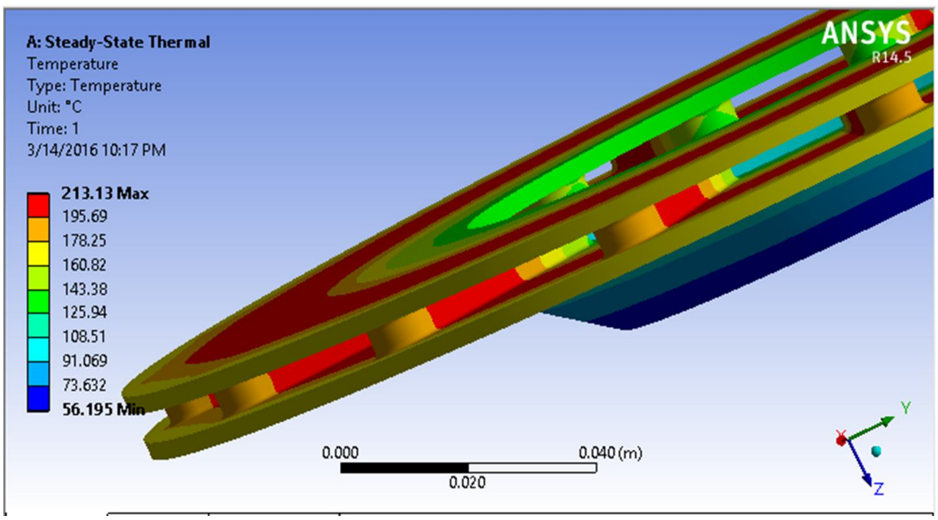

Fig 23: Temperature distribution over the vanes

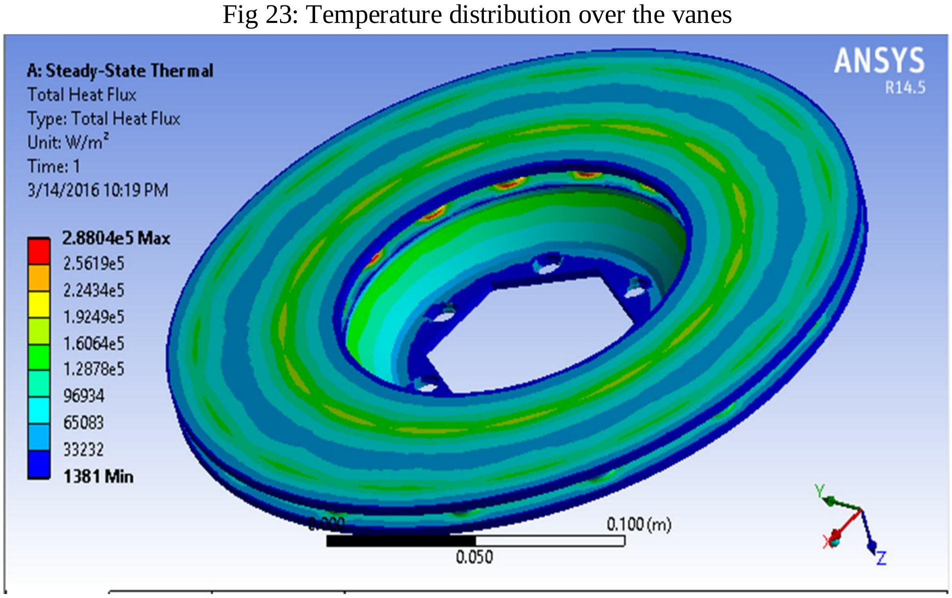

Fig 24: Total heat flux

VI. RESULTS AND DISCUSSION

A. Temperature Distribution

TABLE IV: TEMPERATURE DISTRIBUTION

Rotor	Min Temperature	Max Temperature
Plane	56.618	163.67
Drilled	49.986	154.65
Slotted	54.321	171.22
Vented	56.195	213.13

The temperature distribution over the plane rotor and slotted rotor is almost similar, temperature continuously decrease towards the center of the rotor as there are no holes or major projections on the disc surfaces. The maximum temperatures produced on the discs are 163.67 ^{o}C and 171.22 ^{o}C respectively. The value is greater for the slotted disc because of greater amount of frictional heat produced due to the presence of slots.

The distribution over the drilled rotor is not continuous, the temperature reduces rapidly near the holes due to convection by air passing through the holes. Also the maximum temperature produced is 154.65 ^{o} C, which is lesser than plane and slotted rotors. The distribution over the surface of a vented rotor is similar to plane disc but there is a rapid drop in temperature through the vanes that separate the two rotors.

The maximum temperature values obtained on all types of rotors are below the safe operating value for carbon ceramic disc material of 350 ^{o}C and hence are not prone to brake fade or failure.

B. Total heat flux

TABLE V: TOTAL HEAT FLUX

Rotor	Min Heat flux	Max Heat flux
Plane	514.58	1.2549e5
Drilled	1931.8	2.0759e5
Slotted	2840.2	2.4851e5
Vented	1381	2.8804e5

VII. CONCLUSION

Modelled four different types of disc brake rotor in CATIA. Calculated the total frictional heat generated during braking and performed steady state thermal analysis with carbon ceramic brake material using ANSYS software. Obtained temperature distribution and total heat flux plot over each type of rotor. Effective cooling is found to be better in drilled and ventilated brake rotors in comparison to plane and slotted discs. It is necessary to maintain temperature at a safe operating value to avoid brake fade.

VIII. ACKNOWLEDGEMENT

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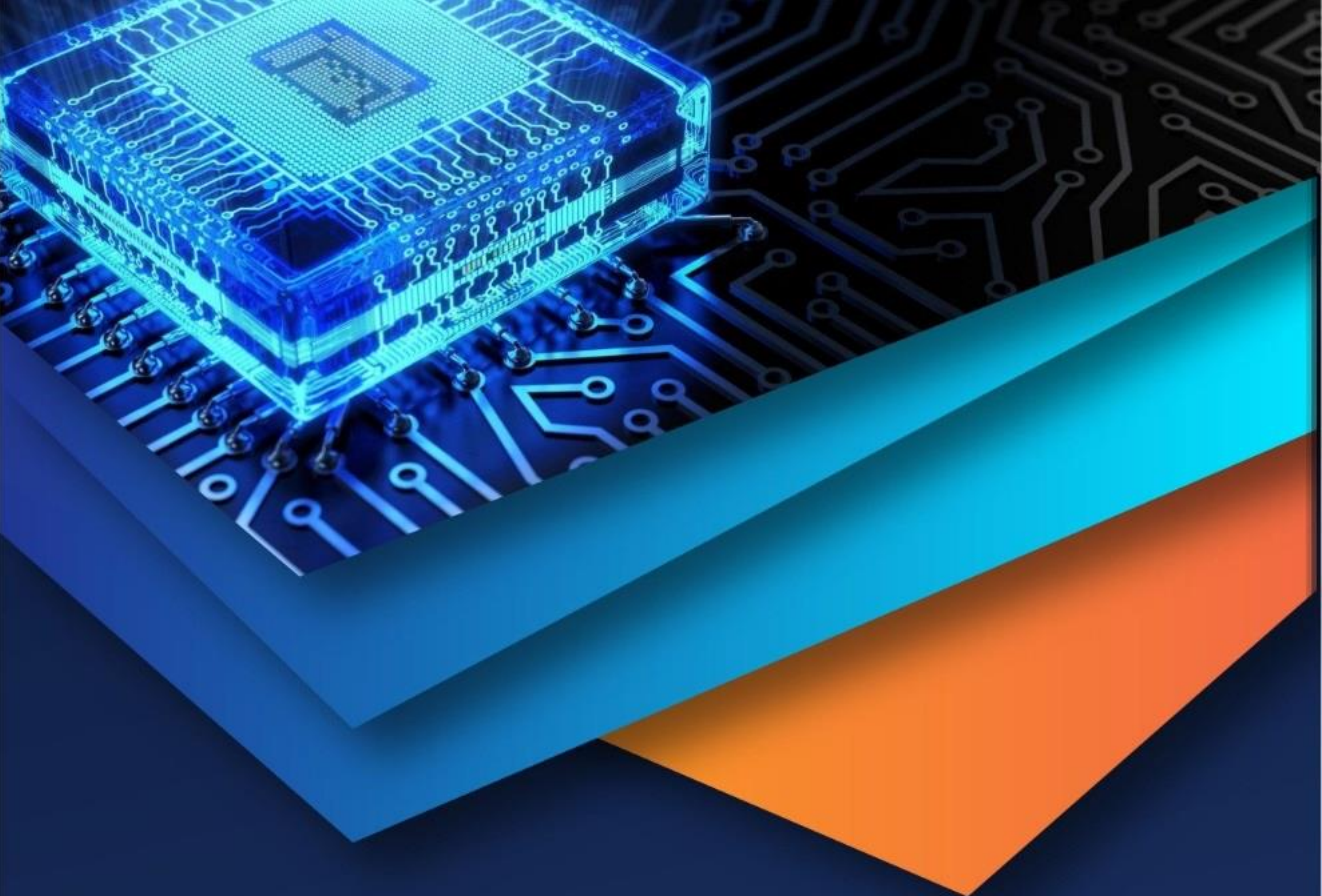

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