Design of Brake Disc with Radial Grooves and its Efficient Cooling System Analysis by Computational Fluid Dynamics Software CFX

Md Sadiq Mohiuddin[1] G.M.Sayeed Ahmed[2]

1. Research Scholar, Mewar University, 2. Research Supervisor, Mewar University, India

Abstract: Braking system performance is an important vital element in an automobile. During the rotation of the disc brake it has to experience sudden change in temperatures while braking and again releasing the brake for attaining speed of the vehicle therefore the amount of heat generated and must dissipates from the brake elements during a small span of time. The absorbed and dissipated heat must be effective in order to attain desirable performance of the braking system. If heat dissipation from the brake disc surface not properly controlled then the excessive surface temperatures within the disc brake become too high and might cause excessive damage to disc surface and also leads to brake pad wear. In scenario of the demand of effective braking applications the radially grooved vanes are incorporated in the brake disc for enhancing the heat dissipation. In order to evaluate and quantifying the application of radial grooves the heat transfer analysis the procedures of Computational fluid Dynamics analysis is applied for obtaining better comparative results of with and without radial grooves. The analysis of domain has been done by using computational fluid dynamics based software CFX. An attempt has been made in this paper is to research the temperature field analysis and air flow characteristics of brake disc with radial grooves. The CFD code CFX was applied to simulate the temperature distribution in the radial grooves domain. A substantial enhancement has been achieved after incorporating radial grooves in the disc surface and the simulations results are confirmed that radial grooves would increase heat dissipation from the brake disc surface.

Key words: Disc Brake, Surface temperatures, CFD, Rotor, CFX, Radial Grooves.

1 .Introduction:A braking system is one among the foremost vital raining a steep hill with a significant load, or perennial safety elements of associate automobile. it's primarily high-speed decelerations, drum brakes would usually fade wont to decelerate vehicles from associate initial speed to and lose effectiveness. Compared with their counterpart a given speed. In some vehicles, the K.E. is in a position disc brakes would operate with less fade beneath an to be reborn to electrical energy and keep into batteries equivalent conditions. a further advantage of disc brakes for future usage. These varieties of vehicles square are their linear relationship between brake force and measure called electrical or hybrid vehicles. However, disc brakes over these forms of vehicles still would like a backup system drum brakes have junction rectifier to their universal use because of typically short electrical energy or failures that on passenger-car and light-truck front axles, several rear inevitably increase the value of the vehicles. therefore axles and medium-weight trucks on each axles. Thus, a friction based mostly braking systems square measure still way to choose higher geometrical style variables and the common device toconvert K.E. into thermal energy, improve thermal performance of automotive brake. through friction between the constraint and therefore the Numerous brake discs are designed in recent years rotor faces. However the impression remains that the advance in Based on the look configurations, vehicle friction cooling characteristics remains comparatively modest. brakes is classified into drum and disc brakes. The drum printed work concentrates on ventilation in terms of brakes use brake shoes that square measure pushed recent shapes for disc vanes and/or pillars, theoretical during a radial direction against a cylinder. comparatively very little is printed in respect to the elemental understanding of the air flow and warmth dissipation, so as to determine methodologies for planning new, higher performance discs. According to the previous analysis one. 1. MirzaGrebovic et al [1], Performance parameters regarding some brake rotors and its face style and repair life. 2. Zhongzhe Chi et al [2], Analyzed the thermal convection is analyzed victimisation associate analytical methodology and rate distribution, temperature contours with different configurations were determined. 3. MesutDuzgun et al [3] , during this study, thermal behaviors of airy brake discs at continuous brake conditions in terms of heat generation and thermal stresses with finite part analysis. The numerical simulation shows ventilation plays a really important role in cooling of the disc within the braking section; during the study they proposed models of disc with vanes under thermal behaviors of different discs brake conditions under heat generation and thermal stresses. Mallikarjuna et al [4], the flow through the ventilated brake rotors are quite complex as it involves both rotating and stationary domains. The fluid regions between the rotating and stationary domains are connected by frozen rotor interface. Turbulence is taken care by SST k-ω model of closure. The rotational periodic nature of the disc brake rotor has enabled the consideration of only a segment of it rather than complete rotor for the analysis. Efficient braking system enables a vehicle to stop smoothly during driving on condition that the vehicle provide essential braking torque to the wheel and at the same time dissipate heat generated by friction between the brake rotor and the pad D.A. Johnson et al [5]. As a result of demand on increasing vehicle speed, weight and acceleration, the necessity for brake disc cooling is also increasing Mohd. ZamriYusoff et al [6]. Efficiency of the disc brake need to be achieved in order to full fill customers demand. Therefore, ventilated disc brake is becoming more essential for better cooling efficiency as it consume a larger area to dissipate heat Marko Tirović et al [7]. Initial flux entering the disc was used to evaluate convective coefficient and stimulate disc temperature variations. We conclude that temperature is influenced by thermal constraints and materials and model, Belhocine A et al [8]. In another study it was mentioned that sudden rise and fall of temperature change in metal parts are due to sliding system. Choi et al. [9].Andinet et al. [10] presented factors influencing braking performance of train during braking time and found major factors are temperatures and friction coefficient between pad and brake disc. Thermal transient analysis of disc braking system was performed to evaluate nodal temperature under different thermal and operating conditions. In this design mounting bell is usually made of a light alloy e.g. aluminum or magnesium. One major advantage of the hybrid brake disc is the relative freedom of expansion of the friction ring which results in lower thermal distortion, T. Deichmann et al [11]. Various methods have been used in the literature to investigate flow field characteristics within brake discs. These are experimental, computational, and analytical. The experimental and analytical methods have severe limitations when applied to brake discs because of limited flow space and complex flow field. The accuracy of mass flowrate and heat dissipation predictions has been vastly improved over semi-empirical predictions by the advances in computational fluid dynamics (CFD); now commercially available codes are capable of giving highly accurate results for the flow field and cooling rate of brake discs [12–13]. The pressure and velocity fields directly affect mass flow characteristics of the disc. This section describes the effect of varying the first row pin profile on the mass flow rate of air passing through the disc at various speeds. Figure 15 clearly shows the effect of increasing the frontal area of the pin on mass flow rates through the disc. It can be seen that increase in the pin thickness results in lower mass rate of flow at a given speed. [14-16]. In 2010, Pevec et al (2) obtained the HTC distribution under different temperature and velocity using a steady-state CFD solver and converted it into the input file of FE model as a surface film condition. [17]. In this paper an attempt has been made to analyze the brake disc with and without radial grooves for flow analysis by considering heat transfer convection only after brake application was completed and car accelerated to regain its original speed. These areas include an effective surface area for applying braking pressure with and without radial grooves on disc surface. The remaining surface area of the disc was considered insulated for the purpose of comparison of surface temperatures with and without grooves under the brake pressure of 1 MPa.

2. Research Methodology

The numerical simulation shows that radial vanes ventilation plays a really important role in cooling of the disc surface within the braking section.CFD Modeling of Brake DISCSCFX is a powerful tool used for analyzing the actual domain by using conventional routines and procedures of CFD in the desired regions.Making Regions and Meshing: In meshing the CFD domain polyhedron element type has been selected. In this step a rotating frame of reference has been created by considering the brake disc and rotor shaft axis. The maraging steel material properties along with the properties of air at 25°C were used in CFX simulation. The CFD simulation procedure includes the turbulent K-ε model with comparatively low pressure gradients. By the application of turbulent model to the domain by using the mesh element shown in Fig 3 used for CFD analyses. The model is exported in IGES format and is employed in CFD tool. Specification of Domain and Boundary Conditions are tabulated in Table: The flow of air through inlet and outlet of the brake disc was analyzed CFX code package.

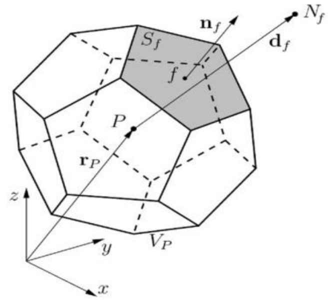


Fig. 1: CFD mesh polyhedral element.

Table 1: Boundary Conditions	
Inlet Conditions	: opening, 0 Pa
Outlet Conditions	: opening, 0 Pa
Angular velocity	: 664 rev/min.
Heat Flux	: 2000 W/m^2 and 4000 W/m^2

The temperature contours are evaluated for different boundary conditions for all discs operative rotation speeds and temperatures, because the brake disc is formed from maraging steel. The disc model is hooked up to associate adiabatic shaft whose axial length spans that of the domain. Air at 250C around the disc is taken into account and openings boundaries with zero relative pressure were used for the lower, higherand radial ends of the domain. A constant angular speed of 664 rev/min and Input Heat flux= 2000W/m2 was employed in a rotating frame of reference regarding the disc and shaft axis. The following is the CFD CFX Solver Methodology includes.

- Flow is be assumed to be steady and incompressible
- Tetrahedral mesh is generated with Boundary Layers
- Moving frame reference is used for the Disc
- CFX solver is used for the study
- Solution is converged to the required level of accuracy,

Standard Fluid properties and boundary conditions Fluid Properties are tabulated in Table

Table 2: Properties of pad and disc

Properties	Disc Brake	Brake Pad
Young's modulus (N/mm^2)	180,000±20,000	1500
Poison ratio	0.3	0.25
Density (kg/m^3)	8–8.1	2595
Thermal conductivity, W/m°C	20±1W/m◦C	1.212
Coefficient of friction	0.35	0.35
Specific heat (J/kg◦C)	450±20	1465

3. Computational Modeling and Simulation Stratagey

The CFD module of ANSYS-CFX is used for mesh generation and simulation is carried out in ANSYS Fluent. The main objective of this study is to understand the distribution of temperature, pressureand velocitywithin passages of radial grooves present in brake rotor configuration. An attempt is made to enhance the convective heat transfer coefficient of radial grooves in brake rotor by understanding the air flow through passages of of radial grooves. Meshing and Boundary Conditions incorporated in 3D model of the radial grooves in brake rotor is imported in IGS format in CFX for mesh generation. The brake rotor is treated as spinning disc in a fluid domain environment and hence open boundary conditions are applied at domain boundary wall. At the inlet and outlet boundary conditions of the domain, pressure of one atmosphere is applied. The computational domain is shown in figure 3, which is large enough to avoid any effect on the flow through passages of brake rotor. Due to rotational and symmetry periodic boundary conditions are applied to either side of the entire rotor. Rotor walls are assumed at constant temperature. The details of boundary conditions and external domain are shown in Figure 4. In order to capture curved surfaces and wall propertiesthe domain is discretized using hexahedral mesh elements Figure 5. Fine meshing has been done near wall to include both the thermal and velocity at the boundary layer. The hexahedral mesh model of disc brake with and without radial grooves is shown in Figure 6. The quality of meshing was done for other issues such as surface orientation, volume. Minimum required quality in order to achieve accurate results and convergence at the earliest. The rotational speed of rotor is assumed to be constant for simulation; therefore a moving reference frame is employed for the CFD analysis. The flow of air is considered to be incompressible and steady.The surrounding temperature and pressure are assumed as 298K and 101.32 Pa. The CFD simulation is carried out by assuming rotor walls at constant and Input Heat flux= 2000W/m^{2}for rotational speed of 664 rev/min. The two fluid zones are created, outer fluid is stationary and while inner fluid is rotating. CFD is the method of solving the fundamental non-linear partial differential equations that govern the heat transfer, fluid flowand turbulence flow. For the present work, CFD simulations are carried using the commercial CFD software package ANSYS CFX. These governing equations are solved by ANSYS CFX at the discretized nodes of the mesh obtained from finite volume method and by applying relevant appropriate boundary conditions as shown in Figure 7. The disc brake being attached to the wheel also rotates at the speed of the wheel of the automobile and the flow inside the rotor is predominantly swirling and rotating. In problems involving rotating motion ANSYS CFX uses method called rotating reference frame, governing equations are solved by considering walls to be stationary in the relative frameand the fluid to be moving with acceleration of the reference frame. The fluid which is flowing around and inside of disc rotor is considered as incompressible and its density is function of temperature because of temperature difference inside the passage of the rotor. The Navier-Stokes equation is then solved by ANSYS CFX using SIMPLE algorithm for pressure velocity terms. The circumferential boundary condition of the brake disc domain is prescribed by a pressure outlet conditions. In order increases the maximum heat dissipation of the brake disc rotor it must be increase in the mass flow rate through the radial grooves to increases the rate of heat dissipation. Mass flow rate depends on density of fluid but due variation of temperature density of fluid keeps on changing which in turn hinders the mass flow rate.Heat transfer from each of the walls can be calculated as a function of the disc surface temperature. The rate of heat transfer from the rotor surfaces can be understood by observing the output Nusselt number distribution.

4. Results and Discussion

To compare the heat dissipation capability of the different configurations of the rotors, the rotor surfaces were assumed to be isothermal temperatures. This temperature was calculated based on the absorption of kinetic energy by rotor immediately when applying the brakes. For each configuration, the nature of the flow-field and heat transfer characteristics is analyzed in detail for different rotational speeds. This may be attributed to the following reasons (i) In the numerical modeling, it is assumed that the rotor surfaces are perfectly smooth, whereas practically it is difficult to achieve a perfectly smooth surface finish. Surface roughness slows down the flow and might have contributed to the variation in temperature distribution across the disc surface. (ii) Atmospheric pressure andtemperatures were assumed to be constant fornumerical predictions (iii) Motor speed was considered to be constant for numerical predictions

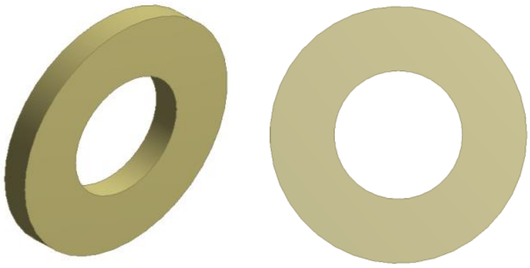


Fig 2:CAD model of brake disc with Radial grooves

Table3: Fluid Domain	
Domain	:Atmosphere
Fluid	: Air
Rotational Speed	: 950 rate
Heat Transfer	:Thermal Energy
Solid Domain	
Domain Name	: Disc
Material	: Gray forged iron
Disc Temperature	: 3000 C
Domain Motion	: Rotating

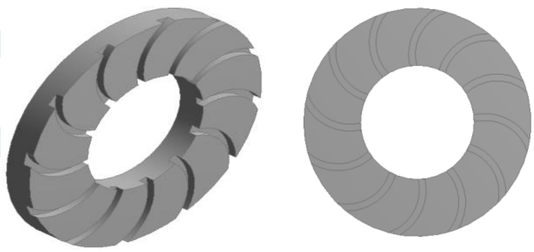


Fig 3: Disc brake disc with and without radial grooves

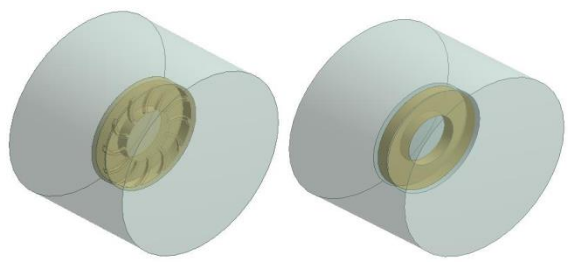


Fig 4: Fluid Domain for Brake disc with and without Radial Grooves

(a) (b)

Fig 5: Meshed Fluid Domain (a) with and (b) without radial grooves

(a) (b)

Fig 6: Meshed for Brake disc (a) with and (b)without Radial grooves

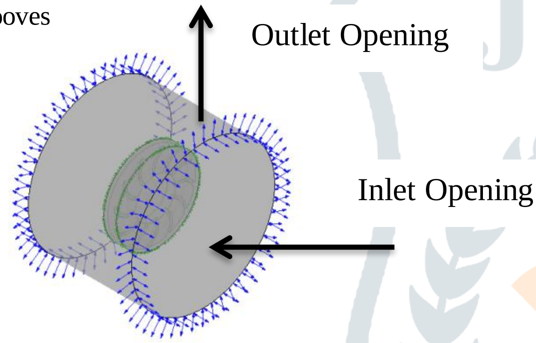
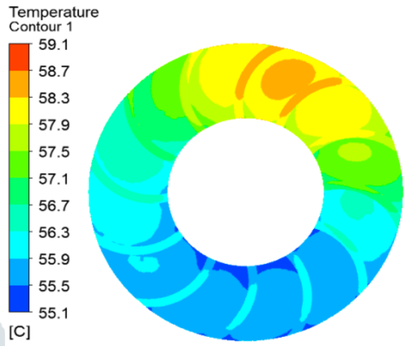


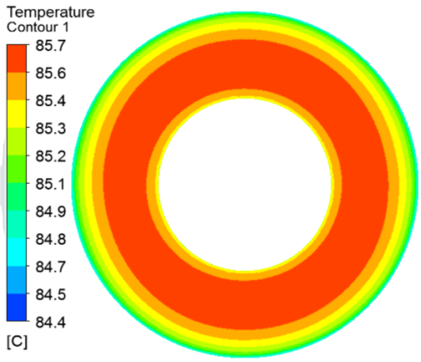
Fig 7: Boundary Conditions in Disc with grooves

Table4: Properties of Brake Disc Material	
Maraging Steel Properties	
Density	: 7854 kg/m^3
Viscosity	: 1.831e-05 kg / m-s
Thermal conductivity:	20 W/mk
Specific heat	: 434 J / kg K

The simulation of the disc surface temperatures, ambient temperature and vehicle speed were able to provide important information for the generation of accurate boundary conditions such as flow of air and brake rotor surface temperature as well as speed of rotation. By the Implementation of boundary conditions that accurately represents the real braking phenomenon temperature contours are evaluated as shown in Figure 8. The heat transfer rate and heat transfer coefficient can be calculated from the basic principal derivative of temperature with respect to time. The temperature of the radial grooves for the inner and outer sliding surfaces of the rotor yields a value for heat transfer rate of 124.7W/m^2K for the heat transfer coefficient.Figure 8 shows the temperature contours in the rotor. The flow pattern shows the formation of vortices at the inlet generated by the flow tumbling over the radial grooves. The flow separates from the leading edge of the grooves after the change in groove outlet angle. The values vary from 200W/m^2K to just below 85W/m2K and the average value is 135.7W/m^2K. This can be explained by the small range in velocity distribution across the vanes passage resulting from the lack the small regions of separation and lack of recirculation. This results in a positive radial velocity distribution across the width and length of the radial grooves giving the rotor a high cooling efficiency. The Wall shear stresses are not having influence in temperatures of the disc surface as shown for radial and without radial grooves presented in Figure 9.The temperature Contours of heat transfer coefficient extracted from the CFD study are presented in shown in figure 10.

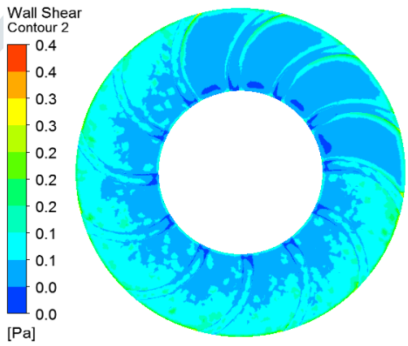


(a)



(b)

Fig 8: Temperature contours (a) with and (b) without radial grooves in break disc with rotation664 rev/min and Input Heat flux= 2000W/m^2



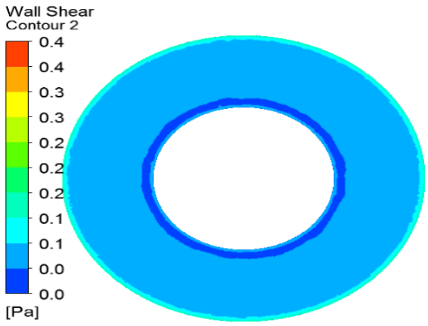


Fig 9: Wall Shear Stress Temperature contours (a) with and (b) without radial grooves in break disc with rotation 664 rev/min and Input Heat flux= 2000W/m^2

The distribution of heat transfer coefficient in the disc is relatively regular when compared to other types of vented brake rotor.values for the average heat transfer coefficient.However it should be noted that conduction to the hub is generally credited as the reason for a difference in temperature between inner and outer rubbing surfaces, due to the large effective thermal mass of the inboard face. This is not represented within the CFD model; therefore caution is needed when making such comparisons. With handed rotors the direction of rotation may have a large effect on the pumping efficiency of the rotor. The early separation of the flow from the leading edge of the vane implies a large adverse pressure gradient. This suggests that when rotated in the opposite direction separation will occur later leading to smaller separation regions; yielding improved thermo-aerodynamic properties.The CFD model over predicted the average heat transfer coefficient and heat transfer rate by 18%, The reasons for the discrepancy between the two data sets can be explained by the simplifications of the real world made by the CFD model.

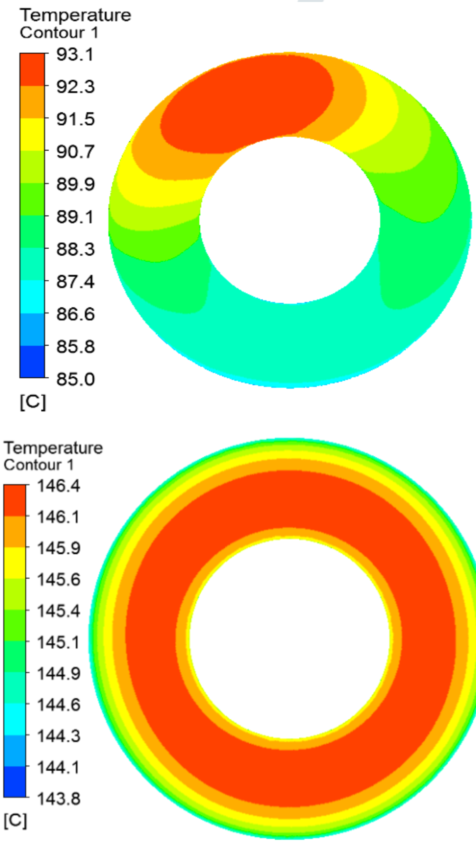


Fig 10: Temperature contours (a) with and (b) without radial grooves in break disc with rotation 664 rev/min and Input Heat flux= 4000W/m^2

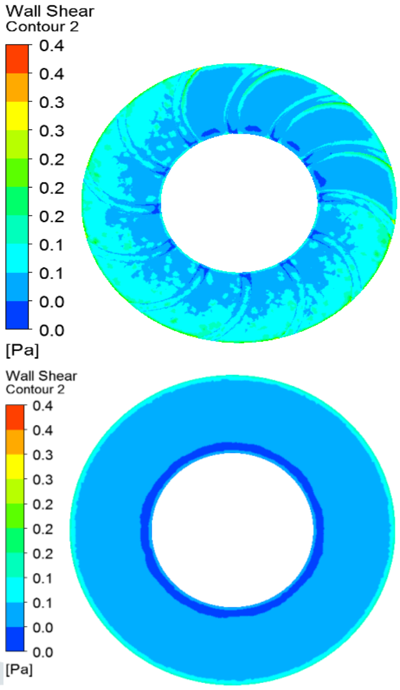


Fig 11: Wall Shear Stress Temperature contours (a) with and (b) without radial grooves in break disc with rotation 664 rev/min and Input Heat flux= 4000W/m^2

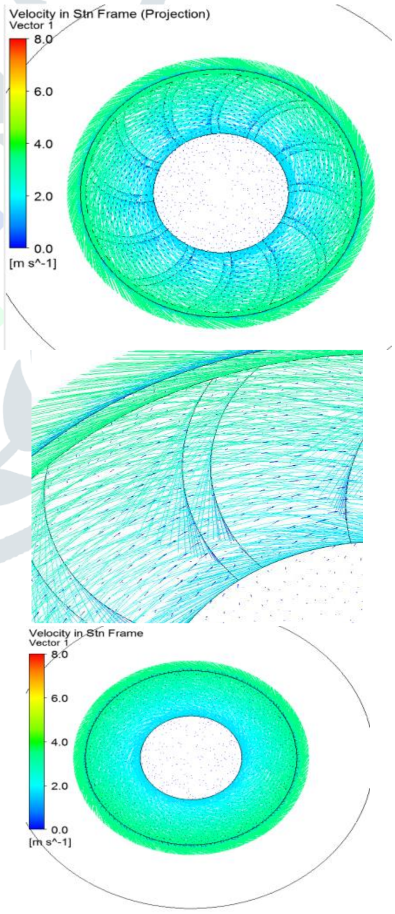


Fig 12: Velocity Vectors for (a) with and (b) without radial grooves in break disc with rotation 664 rev/min and Input Heat flux= 2000W/m^2

Conclusions

This research work presents thermalanalysis of a radially grooved brake model without considering radiation. The analysis is performed using commercial FE software package, ANSYS CFX where the FE model only consists of a disc and two pads. From the single stop braking simulation, it is found that regarding the calculation results, we can say that they are satisfactorily in agreement with those commonly found in the literature investigations. It would be interesting to solve the problem in thermo-mechanical disc brakes with an experimental study to validate the numerical results. The Future work related to disc brake can be done to understand the effects of thermo-mechanical contact between the disc and pads. The recommendations are (1) Study to verify the accuracy of the numerical model developed. (2) Tribological and vibratory study of the contact disc pads(3) Study of dry contact sliding under the macroscopic aspect. The mass flow rate of vented disc brake increases with increase in rpm. Hence, for modern high speed vehicles, radially grooved rotors may be more appropriate. The surface of disc rotor assumed to be smooth but in actual case it is not. A varying heat flux model if incorporated for the rotor surface would closely approximate to actual conditions. Based on the above study the following conclusions are drawn. 1) The recirculation regions in the flow passages reduce convective heat transfer and air mass flow rate through rotor grooved passages. 2) At the recirculation region the air becomes more stagnant which increases temperature at that location and it might promote the hot spots therefore radial groves are proved to be the effective solution for increasing the brake disc life and efficiency.

References

1. MirzaGrebovic, “Investigation of the Effects on considerably exaggerated the cooling rate and Braking Performance of Different Brake Rotor temperature distribution over the disc surface is Designs” in 2007

2. Zhongzhe Chi, 2008. “Thermal Performance Analysis recirculation zones within the flow path are ascertained for and Geometrical Optimization of Automotive Brake eight vanes that ultimately causes energy dissipation that Rotors” in 2008 .

3. MesutDuzgun, 2012. “Investigation of thermostructural behaviors of different ventilation applications on brake discs” in 2012.

4. S. Manohar Reddy, J. M. Mallikarjuna and V. Ganesan, Flow and Heat Transfer Analysis of a Ventilated Disc Brake Rotor Using CFD, journal of SAE, 2008 .

5. A.D. McPhee and D.A. Johnson 2007 Experimental heat transfer and flow analysis of a vented brake rotor International Journal of Thermal Sciences 47 458-467

6. Kannan M. Munisamy, NorshahHafeezShuaib, Mohd. ZamriYusoff andSavithryK.Thangaraju 2011 Flow Streamlining for Cooling Improvement In Ventilated Brake Disc Using CFD As Design Tool Journal - The Institution of Engineers, Malaysia 72 27-35

7. Marko Tirović 2007 Development of Ventilated Brake Discs JUMV International Automotive Conference with Exhibition (Beograd Serbia, 23-25 April 2007)

8. Belhocine, A.; Bouchetara, M. Thermal analysis of a solid brake disc. Appl. Therm. Eng. 2012, 32, 59–67. [CrossRef]

9. Choi, J.-H.; Lee, I. Finite element analysis of transient thermoelastic behaviors in disc brakes. Wear 2004, 257, 47–58. [CrossRef]

10.Eticha, A.K. Analysis of the Performance of Disc Brake System of Addis Ababa Light Rail Transit Using Temperature and Coefficient of Friction as a Parameter. Int. J. Mech. Eng. Appl. 2016, 4, 205–211.

11.T. Deichmann and H. Lathwesen. Sheet cast disc-brake disc innovation through functional integration. Proceedings of the Eurobrake, 16-18 April, Dresden, Germany, 2012.

12. Yeo, T. I., Choi, H., and Kim, J. H. Equivalent axisymmetric finite element applied to undercut shape design of ventilated brake disk. In Proceedings of the IMechE Conference on Brakes 2006, York, UK, 2006, pp. 135–144.

13 Palmer, E., Fieldhouse, J., and Mishra, R. Optimisation of pin shape and its configuration for a ‘pin’ type vented brake disc using CFD. In Proceedings of the FISITA World Automotive Congress, October 2006, paper F2006D115.

14. Daudi, A. and Narain, M. 72 curved fin rotor design reduces maximum rotor temperature. SAE paper 1999-01-3395, 1999.

15. Limpert, R. Cooling analysis of disc brake rotors. SAE paper 751014, 1975.

16. Wallis, L. M. A comparison of bi-directional disc brake rotor passage designs, Australian Digital Theses Program, 2003. 20 Sisson, A. Thermal analysis of vented brake rotors.SAE paper 780352, 1978.

17. Pevec, M., Lerher, T., Potrc, I. and Vranesevic, D., “Numerical temperature analysis of brake disc considering cooling”, Advance Engineering, 4(1), pp. 5564, 2010.