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Review on Thermal Analysis of Ventilated Disc Brake with Different Flow Passages

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Abstract- Safety aspect is considered in top priority while developing a new vehicle. A braking system is must require the component to control and stop a running vehicle. Brake converts kinetic energy into thermal energy, the brakes get too hot with this heat and they may cease to work because they can't dissipate enough heat. The heat generated while braking is stored in brake disc rotor and this heat is dissipated to the surrounding mainly by forced convection. Proper cooling is essential for the efficient braking operation and it can be increased with effective designs of the ventilated disc brake rotor. The brake discs are available in various flow passages such as radial vanes type and pillared vanes type. It is found that thermal failure of disc brake is due to high temperature but it is also seen that high thermal stress develops within rotor passages due to a large temperature gradient. In redial vane rotor temperature distribution within vane, the passage is not uniform and it leads to high thermal stresses. Pillared rotors have more uniform temperature distribution within rotor passages so it may use as best alternative to radial vane rotors. Even though the mass flow rate in pillared rotors is less than in radial type rotors while heat transfer rate is almost same in both. This paper mainly focuses on the understanding of airflow and heat transfer characteristics of some radial and pillared rotors with different configurations. Further results were compared to find best and most effective design of ventilated disc brake rotor.

Keywords: *Thermal stress, thermal failure, straight radial vane, tapered radial vane, diamond pillared rotor, circular pillared rotor.*

I. INTRODUCTION

The important control system of an automobile is braking system. Brakes are used to slow down or stop a moving vehicle as per requirement. Earlier vehicle were fitted with either band brakes or drum brakes. Brake fade and water fade are the main disadvantages of these types of brake. Now in modern age high speed vehicles are in use. Therefore modern automobile requires high speed braking system, especially passenger and racing cars. Drum brakes are inadequate to meet the braking requirements in these conditions. Further in order to reduce un-sprung mass it is necessary to design brakes in smaller size with higher amount of kinetic energy absorption. This heat absorption has increased the area available for heat dissipation is reduced. In result, high temperature in brake disc leads to thermal failures due to cracks and hot spots. In recent years, the stopping capacity of brakes need to be design more accurate and efficient for increasing level of duty requirements. The stopping capacity of brake increases by the heat dissipation rate due to forced convection and thermal capacity of the braking system.

In early age of automobile history drum brakes got used for many years but now in modern high speed vehicles disc brake comes with better efficiency and performance. Drum brakes are not much effective to use in these condition to meet braking requirements. Fig. 1 shows the disc brake rotor, pad and caliper assembly of an automobile. The rotor's temperature may reach very high while braking application. Therefore the disc brake rotor must be able to dissipate heat as fast as possible to perform efficiently with ensuring the life expectancy of the whole braking system.

Figure 1: Disc brake rotor, pad and caliper assembly [1]

The disc brakes rotors are solid and ventilated type. Modern high speed vehicles have fitted with ventilated type disc brakes. The ventilated disc rotors are mainly used to enhance cooling performance and its operation seems to be similar as centrifugal impeller. Ventilated disc rotors have more surface area and less mass over solid disc rotors so that ventilated discs are recommended to use in automobiles. The mass flow and heat dissipation rate of disc brake rotors depend upon various parameters such as geometry of rotor and flow passages, air flow rate through ventilated passages, air turbulence etc.

The brake rotors are mainly differentiate into radial type and pillared type brake rotors. Radial type disc brakes are easy to be manufactured as compared to pillared rotors but after that it has more thermal and structural advantages over the radial brake rotors. The material distribution is more uniform in pillared rotors over the radial rotors which provide resistance to crack propagation. In case of straight radial vane rotor passages the pressure, velocity and temperature distributions is not uniform which leads to high thermal stresses. [2] These parameters and heat transfer rate from the rotor passages is symmetrical in case of pillared rotors. That is why ventilated pillared rotors may be more appropriate as compared to straight vane rotors for modern high speed vehicles.

II. PREVIOUS WORK

Limpert, Rudolf [1975] compared the cooling performance of solid and ventilated disc brake rotor. They found that solid rotors exhibits larger convective heat transfer coefficient than that produced by ventilated rotors. Approximately one third cooling from the vanes and two third from the friction surface exposed to the ambient air consist in total convective heat transfer coefficient. At high speed of rotor almost 50-60 percent contribution of total cooling belongs to internal cooling. The larger surface area of ventilated disc rotor is the major factor for reduced temperature. [3]

T. Valvano and K. Lee [2000] investigated thermal distortion under steady state or transient conditions for a disc brake rotor. They used an analytical method to determine heat input and cooling characteristics with resultant distortion and stress components for a brake rotor. In their investigation method they have used a computer program to calculate the necessary thermal parameters and the result is carried as input for a finite element based thermal stress analysis. They developed a methodology to investigate heat input and cooling characteristics of a brake system in addition to resultant distortion and stress components in a disc brake rotor. To calculate the frictional heat inputs to the rotor and pads of disc brake they have used a computer based tool. The brake corner finite element model is to calculate thermal stress and distortion for disc brake rotor and brake pads is shown in Fig 2. [4]

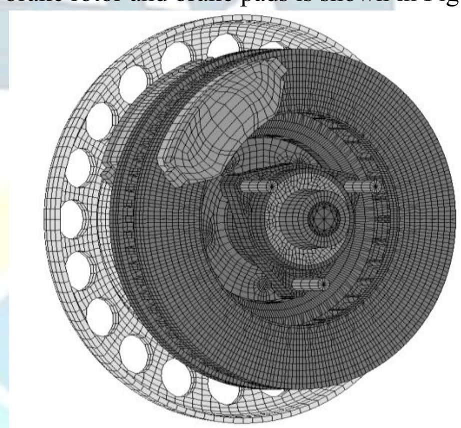

Figure 2 Model - Brake Corner Finite Element [4]

Lisa Wallis, Eddie Leonardi, Brian Milton & Phillip Joseph [2002] compared three different designs of ventilated disc rotors and observed the air flow and heat transfer rate through the internal ventilated passage of them. The three models used in their study are SRV ventilated rotor, SRV-R (SRV rotor with rounded vanes) and ventilated rotor with DTDP instead of vanes. The SRV-R rotor gives approximately 19% more mass flow rate than that for the DTDP rotor at a speed of 20 rad/s and 12% more for speed of 40 rad/s and above through their internal ventilated passage. The SRV-R rotor gives 24% more mass flow than that the SRV rotor at a speed of 20 rad/s and up to 39% more at a speed of 100 rad/s.[5] The geometries of rotors used for their study are showing in Fig 3.

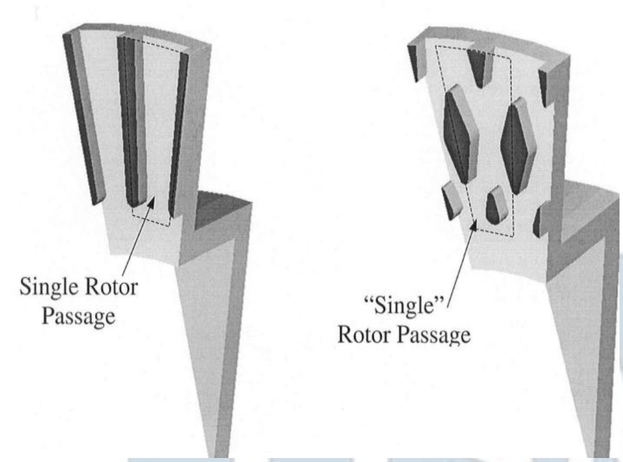

Figure 3: 20º Segments of SRV-R and DTDP Rotors [5]

A D Mcphee, and D A Johnson, [2008] suggested an analytical and experimental methodology to understand the convection heat transfer through the ventilated flow passage of a disc brake rotor. The flow patterns were observed by using PIV (particle image velocimetry) method to determine the presence of recirculation zone on the suction side and the velocity field. Fig 4 shows the results at a speed of 684 rpm, subjected to counter-clockwise rotation of disc rotor. [6] Flow patterns, entrance effects and the presence of recirculation on the suction side were observed by this figure.

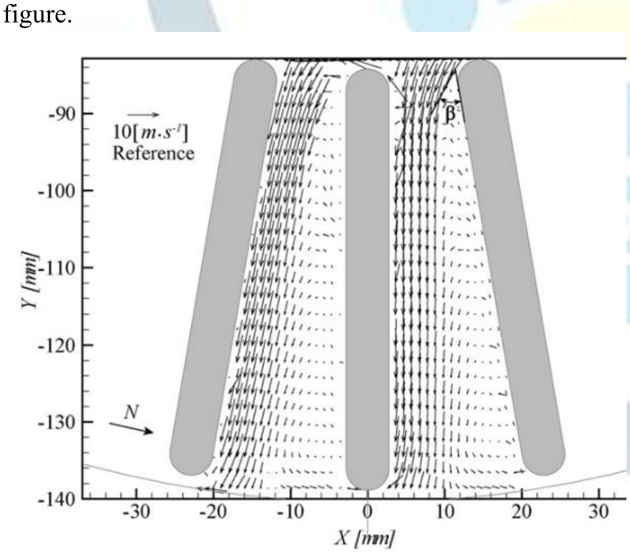

Figure 4: Phase-averaged relative velocity field for ventilated disc rotor at 684 [rpm] [6]

Faramarz Talati, Salman Jalalifar [2009] **c**onsidered conduction mode of heat transfer in their study and extracted the governing heat equations for the disc rotor and pad in the form of transient heat equations with heat generation and that is time and space dependent. [7] The used finite element method to investigate the conduction heat transfer in a high performance passenger car's disc brake system in their earlier paper (Talati F. and Jalalifar S. 2008). They highlight the adverse effect of heat conduction on brake components and suggested to utilize an appropriate DOT rating fluid. [8]

Ali Belhocine, & Mostefa Bouchetara, [2012] presented a numerical simulation method for the thermal behavior of a full and ventilated disc brake rotor in transient state. Using the computer code ANSYS 11 they were able to study the thermal behavior of three types of cast iron (AL FG 25, FG 20, FG 15) for a determined braking condition. They also studied the influence of the braking modes on the thermal behavior of the discs brake. The numerical simulation in their study shows that radial ventilation plays a very significant role in cooling of the disc in the braking phase. The obtained results are very useful for the study of the thermo-mechanical behavior of the disc brake rotor. [9] In their another next paper (Belhocine, Ali & Bouchetara, Mostefa 2012) they have presented the analysis of thermo- mechanical behavior of the dry contact between the brake pads and disc rotor during the braking process. [10]

S. Manohar Reddy, J. M. Mallikarjuna and V. Ganesan [2013] used six types of bi-directional configurations of disc brake rotor (i.e. which can be used for both sides – left & right) for their investigation of cooling performance through ventilated flow passages. The analysis was done using FLUENT, a CFD code. In their earlier paper (S. Manohar Reddy, J. M. Mallikarjuna and V. Ganesan 2008) they describe the numerical simulation of the flow and heat transfer around a ventilated brake disc. [11] The 20º segment of the rotor which has 36 passages is modelled for analysis. The configuration used for analysis are straight radial vane (SRV), tapered radial vane (TRV), diamond pillared (DP) and circular pillared (CP) shown in Fig 5. The purpose of development of pillared rotor is to get advantages of curved vane rotors and to satisfy bi-directionality. The geometry of rotor was designed in such a way that ventilated passage at inlet and outlet of the passages

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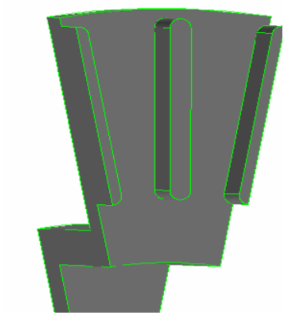
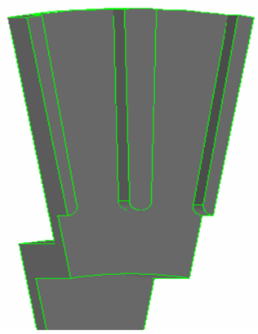
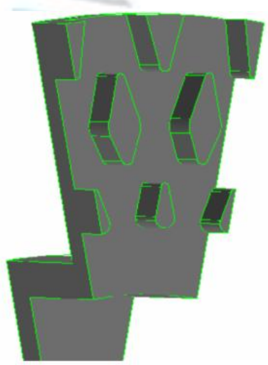
are almost the same for all configurations. Rotational speed of rotor is considered between 800 to 1800 rpm which is approximately 90 to 180 km/h for a typical four wheeled automobile.



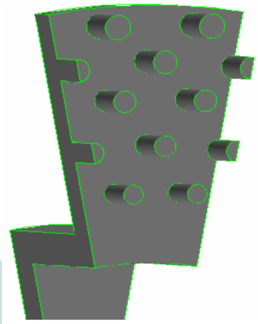
Straight Radial Vane (SRV)



Tapered Radial Vane (TRV)



Diamond Pillar (DP)



Circular Pillar (CP)

Figure 5 Configurations of Ventilated Disc Brake Rotor [12]

The distribution of pressure, velocity and temperature of air in vane passages of radial vane rotor is uneven. At the trailing edge of passage, the pressure is less and it increases as we go towards leading edge. A circulation region found at the outlet of leading edge, which cause a reduction in air mass flow rate. Fig 6 shows the pressure distribution within passages of radial vane rotor. High thermal stresses are generated across leading and trailing edge of passage due to uneven distribution of pressure, which leads to thermal failure of brake rotor. This non uniform temperature distribution is responsible for cracks, hotspots on rotor surfaces. Generally hot spots are generated where a very high temperature, >700 °C, concentrated at smaller region.

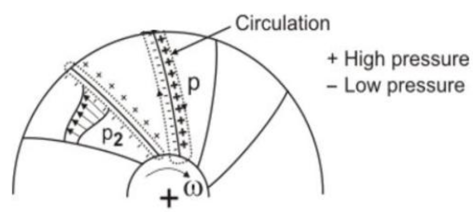
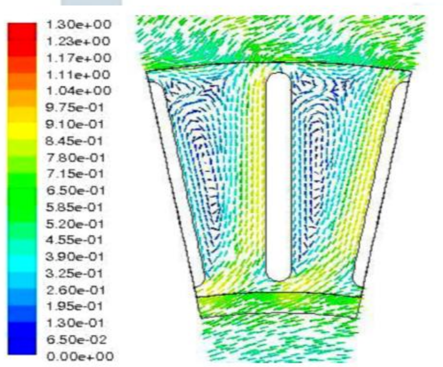


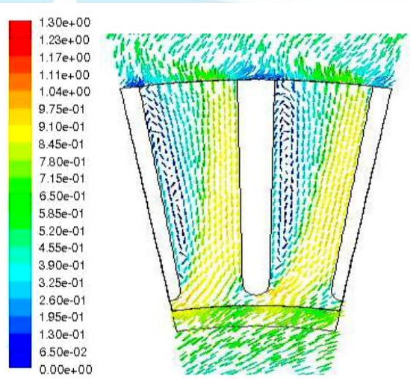
Figure 6 Uneven Pressure Distributions in Rotor Passages of Radial Vane Rotor

In comparison with radial vane rotors, pillared rotors have more uniform temperature distribution within the rotor passages, therefore they are able to sustain in a higher temperature. Due to this advantage of pillared rotor their life is more as compare to radial vane rotor and they can be suitable for modern high speed vehicles. The uniform material distribution within rotor passages of pillared rotor provides better cracking resistance.

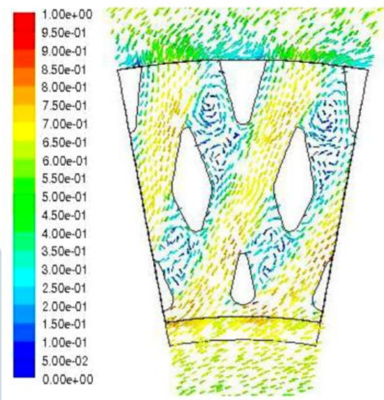
A CFD analysis on various ventilated rotor configurations has been performed by S. Manohar Reddy, J. M. Mallikarjuna and V. Ganesan 2008. The non dimensional relative velocity vectors at the mid-plane of the passage of different rotors at 1800 rpm of their investigation are shown in Fig 7. It is observed that the recirculation region at the leading edge is reduced by modifying vane design from SRV to TRV. Therefore the mass flow rate of air is increased approximately 33 % for tapered radial vane (TRV) in comparison with straight radial vane (SRV) at 1800 rpm. It is also observed that velocity distribution for pillared type rotor is more uniform as compared to radial vane and other ventilated rotors. [12]



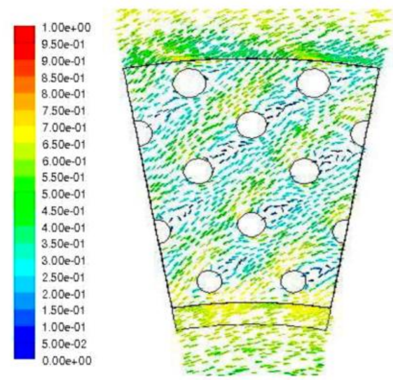
Straight Radial Vane (SRV)



Tapered Radial Vane (TRV)



Diamond Pillar (DP)



Circular Pillar (CP)

The cooling performance of disc brake rotor not only depends on mass flow rate, it also depends on flow passage geometry. For uniform heat dissipation from the rotor surfaces, the uniform distribution of mass flow rate in the passage is necessary. At the rotational speed of 800 rpm and at temperature of 700 K the mass flow rate, overall heat transfer coefficient and heat dissipation per passage through 20º segments of different rotor configurations are shown in table 1.

Table 1: Comparison of Different Ventilated Disc Brake Rotor

Type of Rotor	Mass flow rate (g/sec)	Heat Transfer Coefficient (W/m2K)	Heat Dissipation (W)
SRV	1.4	32.81	217.12

TRV	2.04	45.26	295.12
DP	1.51	42.11	279.15
CP	0.72	32.71	216.13

From the above table, it is observed that the TRV rotor has higher mass flow rate and heat transfer coefficient over other rotor configuration. The mass flow rate through passages of tapered radial vane (TRV) rotor is approximately 26 % greater than diamond pillar rotor. Diamond pillar (DP) rotor has lower mass flow rate than tapered radial vane (TRV) rotor, the heat dissipation is approximately same for both configurations. The air flow through ventilated passages of diamond pillar (DP) rotor is more uniform than tapered radial vane (TRV) rotor. It is expected that the thermal gradients within passages of diamond pillar (DP) rotor will be less and temperature distribution is more uniform in comparison with tapered radial vane (TRV) rotor. [12]

III. CONCLUSION

In the present study, the thermal characteristics of different brake rotors are compared. From this it is concluded that overall heat dissipation of ventilated disc brake rotor is highly dependent on geometrical design of flow passage of disc brake rotor. After reviewing all the previous studies, the following conclusions are drawn:

- Pillared rotor has more uniformed mass flow rate and heat transfer than radial rotors.
- Diamond pillared (DP) rotor passages has 26% lower mass flow rate than tapered radial vane (TRV) rotors. Therefore DP rotor has a noticeably lower mass flow rate than TRV rotor and the heat dissipation through flow passages is approximately same for both configurations.
- The heat dissipation through the flow passage of diamond pillar (DP) rotor is about 30 % more than circular pillar (CP) rotor; hence diamond pillar (DP) may be more appropriate than circular pillar (CP) rotor.
- Diamond pillared (D) rotor has more uniform airflow through passage than tapered radial vane (TRV) rotor configuration. In results, temperature distribution in passages of diamond pillar (DP) brake rotor found more symmetrical, which leads to lower temperature gradients across rotor surfaces.
- The brake rotor design should not be fully dependent on heat transfer rate; it should also be based on the uniform heat dissipation from rotor surfaces.
- It is concluded that the diamond pillar (DP) brake rotor may be more appropriate for modern high speed automobiles due to uniform and higher heat dissipation characteristics.

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