International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 1, January - 2014

A Technical Review on "Effect of Different Disc Brake Rotor Design on Braking Performance"

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***Abstract*— Braking is a process which converts the kinetic energy of the vehicle into mechanical energy which must be dissipated in the form of heat. During the braking phase, the frictional heat generated at the interface disc-pads can lead to high temperatures. This high temperature rise of the rotor reduces the coefficient of friction between pad and rotor, which reduces braking efficiency. Excessive thermal loading can also result in surface cracking, judder and high wear of the rubbing surfaces. High temperatures can also lead to overheating of brake fluid, seals and other component. Thus, how to select better geometrical design variables and improve thermal performance of automotive brake rotors is a task that the vehicle designers and researchers are often confronted. For this review paper, work done in this field by different author is reviewed and it is concluded that vented rotor is best rotor design and vane number have greater effect in heat removal capacity of vented rotor.**

***Index Terms*—Disc brake rotor, temperature rise, braking performance.**

INTRODUCTION

A brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a machine. In the process of performing this function, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators etc. The energy absorbed by brakes is dissipated in the form of heat. This heat is dissipated in to the surrounding atmosphere. Excessive thermal loading can result in surface cracking, judder and high wear of the rubbing surfaces. High temperatures can also lead to overheating of brake fluid, seals and other components. Based on the design configurations, vehicle friction brakes can be grouped into drum and disc brakes. The drum brakes use brake shoes that are pushed in a radial direction against a brake drum. The disc brakes use pads that are pressed axially against a rotor or disc. Under extreme conditions, such as descending a steep hill with a heavy load, or repeated high speed decelerations, drum brakes would often fade and lose effectiveness. Compared with their counterpart, disc brakes would operate with less fade under the same conditions. An additional advantage of disc brakes is their linear relationship between brake torque and pad/rotor friction coefficient. Advantages of disc brakes over drum brakes have led to their universal use on passenger-car and light-truck front axles, many rear axles, and medium-weight trucks on both axles.

PROBLEMS ASSOCIATED WITH OVERHEATING BRAKES

If the temperatures reached in braking become too high, deterioration in braking may result, and in extreme conditions complete failure of the braking system can occur. It can be difficult to attribute thermal brake failure to motor vehicle accidents as normal braking operation may return to the vehicle when the temperatures return to below their critical level One of the most common problems caused by high temperatures is brake fade; other problems that may occur are excessive component wear, rotor deterioration, and thermally excited vibration (brake judder). Heat conduction to surrounding components can also lead to damaged seals, brake fluid vaporization, as well as wheel bearing damage, while heat radiated to the tyre can cause damage at tyre temperatures as low as 200°F (93°C).

DISSIPATION OF HEAT FROM DISC BRAKE

The rise in temperature of the brake disc in any braking operation will depend on a number of factors including the mass of the vehicle, the rate of retardation, and the duration of the braking event. In the case of short duration brake applications with low retardation, the rotor and friction material may absorb all of the thermal energy generated. As a result very little heat dissipation occurs as the temperature rise in the rotor is minimal. In extreme braking operations such as steep descents or repeated high speed brake applications, sufficient heat dissipation becomes critical to ensure reliable continued braking. As the rotor temperature rises it begins to dissipate heat, at steady-state conditions heat generated through braking equals heat dissipation and not further heating occurs. If the heat generation is greater than the dissipation then the temperature will rise, the rate of this rise will depend of the relative quantities of each. If sufficient heat dissipation does not occur the temperature of the rotor and friction material can reach critical levels and brake failure may occur. Heat dissipation from the brake disc will occur via conduction through the brake assembly and hub, radiation to nearby components and convection to the atmosphere. At high temperatures heat may create chemical reactions in the friction material, which may dissipate some of the braking energy.

However research conducted by Day and Newcomb (1984) indicated this to be less than two per cent of the total energy dissipated. While conduction is an effective mode of heat transfer it can have adverse effects on nearby components. Such effects include damaged seals, brake fluid vaporization, as well as wheel bearing damage. Radiation heat transfer from the rotor will have its greatest effect at higher temperatures but must be controlled to prevent beading of the tyre. It is estimated that the amount of heat dissipation through radiation under normal braking conditions is less than 5% of the total heat dissipated.

DIFFERENT PARAMETER'S INFLUENCE ON TEMPERATURE PERFORMANCE

1. INFLUENCE OF ROTOR MATERIALS

The thermal properties of brake rotors are dependent on the temperature and materials with different properties. Newcomb [1] revealed that the thermal properties vary linearly with temperature as indicated in the following equations.

$$k = k_i(1+K1T)$$

$$c\rho = c_i\rho_i(1+K1T)$$

Newcomb [1] investigated the thermal properties of rotors with different materials involving cant iron, steel, aluminum bronze and duralumin. Based on above equations, the temperature distributions can be calculated for various alloys as shown in figure.

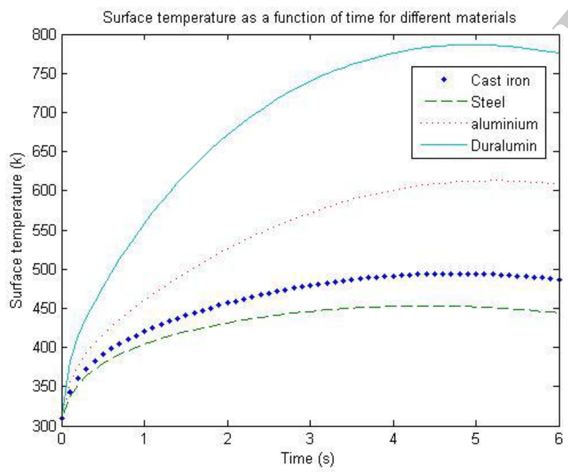

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Figure1. surface temperature as a function of time for different material

As shown in above figure, the steel rotors have the lowest temperature among these four materials and the duralumin rotors have the highest temperature. But the cost of the steel rotor will be higher, so cast iron is still the preferred material.

But the wear resistant property of cast iron is not good so researcher have used coating for wear resistance on cast iron rotor [2,3].

2. INFLUENCE OF THICKNESS AND RADIUS OF ROTOR .

As we have seen earlier that most of heat removal take place because of the convection and equation for the convection is

$$Q = hA(T_c - T_\infty)$$

Where, h=convection heat transfer coefficient. A=surface area of rotor. T_c and T_∞ is rotor surface temperature and ambient air temperature respectively.

So for more heat convection we will need to increase the surface area of the rotor. Which we can increase by using higher thickness or higher radius rotor.

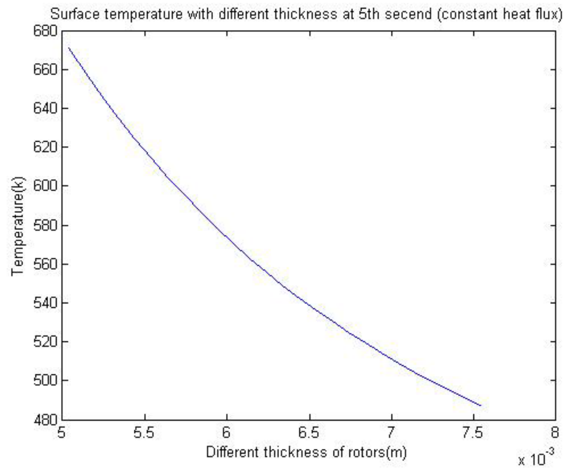

Figure2. Surface temperature with different thickness at 5th second (constant heat flux.)

But surface area increase is restricted by the wheel diameter. Also weight of the disc brake system will increase, so for maximizing the rate of heat transfer manufacturer are using the different material for rotor which will have the higher convection heat transfer coefficient, as we discussed earlier the material can be used also have limitation. So now research is going on to improve the flow of air around the rotor for better cooling.

3. INFLUENCE OF GEOMETRY OF ROTOR.

Earlier disc brake used had solid rotor, afterward disc brake rotor geometry evolve from just solid rotor to cross drilled, slotted rotor and combination of them. Solid rotor is the basic design and has advantages compare to cross drilled, slotted design. Blank design is more resistant to cracking & deformation compare to the other geometry. But for the high powered automobile and heavy vehicles, manufacturer needed brake which can stop the vehicles in very less time. For that they needed the rotor which can remove the heat, generated during braking in very short time. Because of the material evolution, stress was not the factor so they started designing the rotor for better cooling to keep the braking performance intact even at higher temperature. Then came vented rotor's which had the better cooling performance then the solid rotor. vented rotor have small passage between two solid plate and air can flow through it, that's how we get the better cooling. Flow of air through the passage will increase with increasing the rotational speed. Limpert [4] compared solid and ventilated rotor thermal performance at higher rotor speeds, wherein the internal cooling may contribute as much as 50 or 60 percent to the total cooling .Now the research is done to further improve the geometry of the vented rotor. Parish and MacMauns[5] revealed the effects of disc geometry and rotating speed on the mean flow, passage turbulence intensity, and mass flow. The aerodynamic characteristics of the mass flow were found to be reasonably independent of rotational speed, but highly dependent upon rotor geometry.

4. INFLUENCE OF VENTILATED BRAKE ROTOR AERODYNAMICS

The aerodynamics of a ventilated brake rotor is complex and highly dependent on the geometry of both the brake rotor and its surrounding environment. As we have understood that ventilated rotor behaves as a centrifugal fan, drawing cool air from the inboard side, passing through the rotor passages and exhausting at the outer diameter, researcher have studied the aerodynamics of conventional centrifugal impellers extensively from pumping performance and efficiency point of view . Earlier work was measuring of the rotor exit airflow using pressure probes for velocity profile and calculation of the rotor mass flow.

Barigozzi[7] is one of the few previous workers who used hot -wire anemometry (HWA) to examine the unsteady rotor exit flow field for two disk geometries featuring a)backward curved vanes and a b)pedestal arrangement.

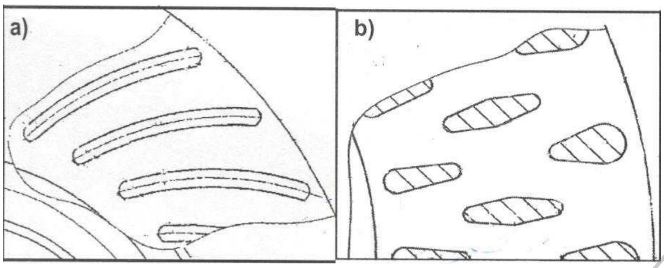

Figure3.a) backward curved vanes &b) pedestal arrangement.

He showed that the pedestal configuration increased both the non - dimensional mass flow as well as the reported turbulence intensity.

Johnson[6] used two -component PIV system and revealed a large area of separated flow within passages where the air changes route from both axial to radial and also tangential to radial.. Other workers have shown that both local geometry modifications to the rotor inlet and cross drilled holes can have a beneficial effect on the cooling performance.

Hudson[8] did design modification for the progress of the mass flow rate through rotor passage. He considered the radial blades for analysis; to impart the pre-rotation for avoiding turbulence he changed the design to direct the flow into the rotor vanes via an inducer (as seen in below figure)

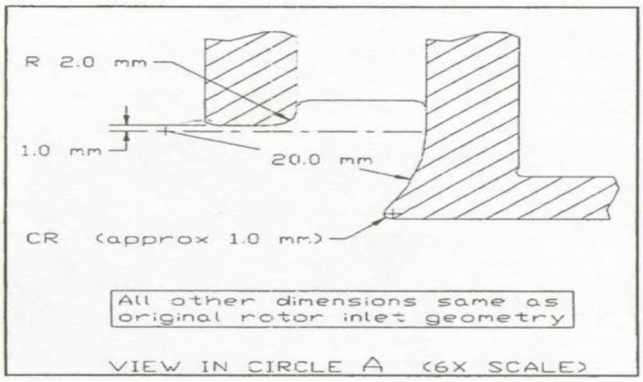

Figure4. modified design at the inlet of rotor.

REVIEW OF THE RESEARCHERS WORK

Zhongzhe Chi.[9,10,11] He did the analysis for the thermal performance and optimize the geometry of rotor. He used the commercial FLUENT software to determine the effects of geometrical parameters of rotors on thermal performance of disc brakes. These geometry parameters included were vane angles and vane numbers.

He choose five different rotors with 24,32,40,50 and 60 vanes to see the effect of vane no. on heat transfer rate. Then plotted graph on outcome of the analysis which is shown below.

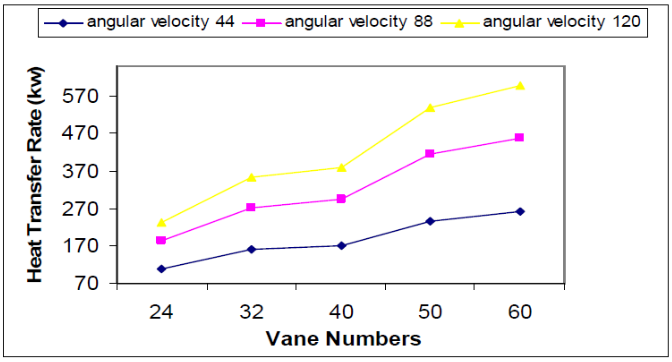

Figure5. Effect of vane number on heat removal rate.

To find out the effect of vane angles on the heat transfer rate he modeled and analyzed rotor with different vane angles (10^0,20^0,30^0 & 40^0). Graph plotted on outcome looked like this.

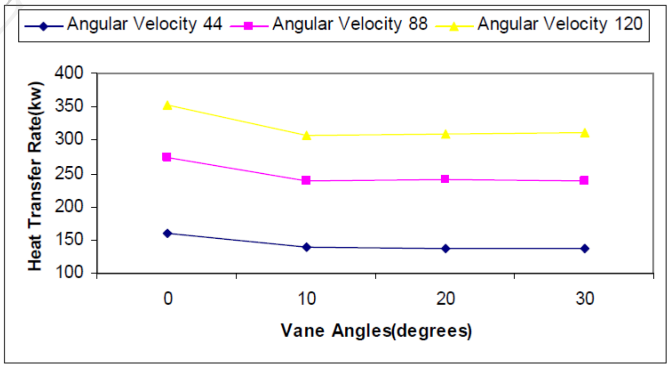

Figure6. Effect of vane angle on heat removal rate.

In overall he found that when vane numbers from 32 to 60 thermal performance increase by 63.5%, 67.9% and 69.2% at an angular velocity of 44, 88 and120 radian per second respectively. The vane angles do not contribute to the improvement of thermal performance for small vane number but improves with increase in the vane number.

Bu-Byoung Kang et al.[2]They needed to develop new brake disc materials with higher frictional performance and longer service life to speed up the train and reduce the maintenance cost. Alternative was ceramic material but bulk ceramic materials show low fracture toughness and difficulty in fabricating to the required shape. So they used Plasma spraying technique for thick ceramic coatings and tested two coated brake discs and one steel disc under the same experimental conditions on a reduced scale braking test bench.

The outcome of the experiment was that ceramic coated discs had shown good stability in friction coefficient at high speed and high energy braking conditions. But Ceramic coated discs caused more pad mass wear loss than the steel disc. On other hand Steel disc had shown fluctuating friction coefficient at high speed and high energy braking conditions, but less pad mass wear loss than ceramic coated discs.

A.D. McPhee et al.[13] They employed experimental and analytical method to understand convection through fins of brake rotor. The experimental approach involved two aspects, assessment of both heat transfer and fluid motion. A transient experiment was conducted to quantify the internal (fin) convection and external (rotor surface) convection terms for three nominal speeds. They considered only convection; conduction and radiation were determined to be negligible. Rotor rotational speeds of 342, 684, and 1025 [rpm] yielded fin convection heat transfer coefficients of 27.0, 52.7, 78.3 [$Wm^{-2} K^{-1}$], respectively, indicating a linear relationship. At the slowest speed, the internal convection represented 45.5% of the total heat transfer, increasing to 55.4% at 1025 [rpm].

Belhocine Ali et al.[12] They did the analysis of thermomechanical behavior of the dry contact between the disc and pads during the braking phase; modeling was based on the ANSYS 11.0. They shown that ventilation system plays great role in cooling disc. Their analysis results shown that temperature field and stress field in the process of braking phase were fully coupled. The temperature, Von Mises stress and the total deformations of the disc and contact pressures of the pads increase as the thermal stresses are additional to mechanical stress which causes the crack propagation and fracture of the bowl and wear of the disc and pads.

Conclusion

For the high speed and heavy vehicle, brake rotor with the coating of wear resistance material is good option. From vane and pin configuration rotor, pin rotor give high mass flow rate and create turbulence inside the passage for better convection but its manufacturing cost will be higher than the vented rotor. so vented rotor is better choice, vane number have greater influence on heat removing than other parameter. Vane angle don't play too much role, so instead of that we can use the Hudson's design of directing the flow at the entrance of the air into the rotor.

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