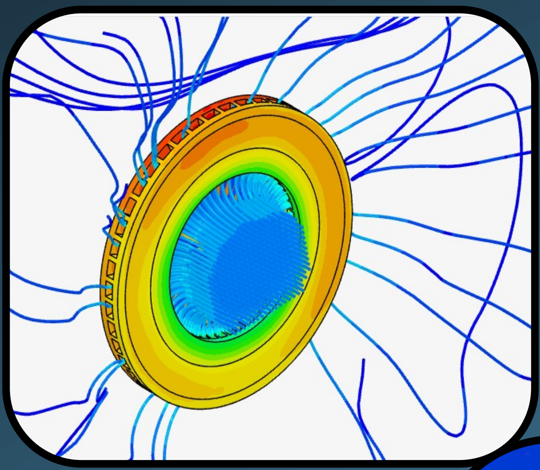
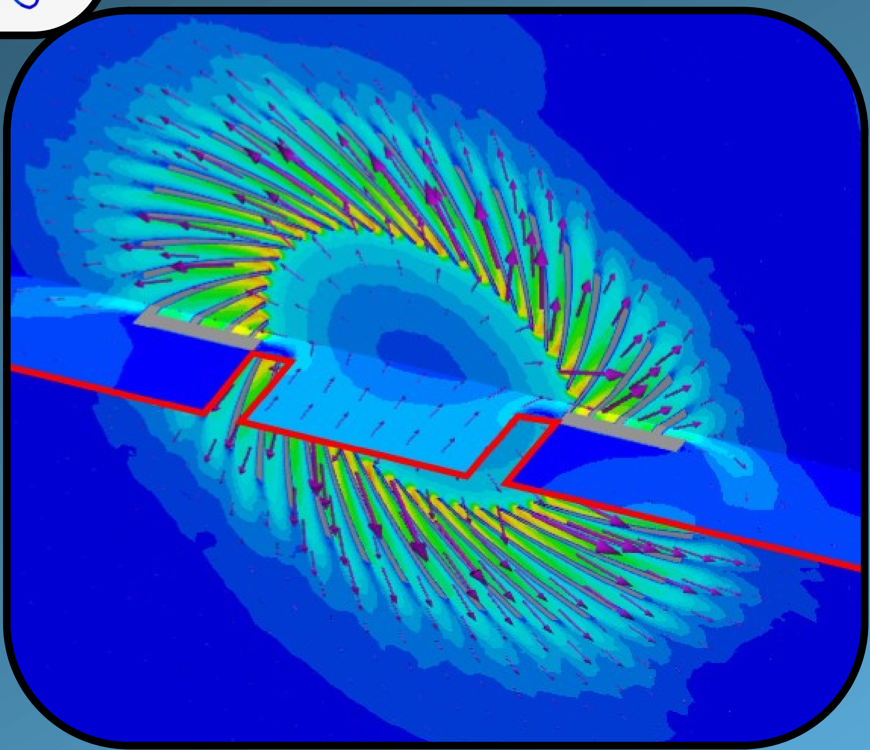
Comparative Thermal Analysis of Radial and Directional Disk Brakes under High-Speed Operation:
A Conjugate Heat Transfer Study





By-

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Introduction

The disc brake is a critical component in vehicles, exposed to non-linear transient thermoelastic conditions. It uses calipers to squeeze pairs of pads against a disc or a rotor to create friction. This action slows the rotation of a shaft, such as a vehicle axle, either to reduce its rotational speed or to hold it stationary. The energy of motion is converted into heat, which must be dispersed.

Ventilated brake discs, also known as vented discs, are a common type of brake disc used in modern vehicles due to their superior heat management capabilities. These discs feature two 'faces' spaced apart, creating room for cooling channels that allow heat to escape. This prevents the disc from overheating and cracking, thereby increasing the lifespan of the brake pads.

Over the years, the design of ventilated discs has evolved to improve airflow. The ventilation channels can be straight, curved, or even formed into various 'pillar' style designs. Each design variation offers unique advantages in terms of heat dissipation and braking performance. In addition to standard vented discs, there are also cross-drilled and slotted or grooved ventilated discs. Cross-drilled discs have holes drilled through them to allow gases to escape and reduce weight. Slotted or grooved discs have slots or grooves on the surface to allow gases to escape, clean the pad, and increase friction.

This project presents a conjugate heat transfer analysis of two disk brake rotor types, a critical component of a disk brake system. The primary objective is to investigate the heat dissipation process from the disk, with a particular focus on the influence of airflow. The study is grounded in the principles of thermo-fluid dynamics, which combines the fields of thermodynamics and fluid dynamics. A unique aspect of this project is the incorporation of a Moving Reference Frame (MRF) to account for the rotational velocity of the disk. This inclusion provides a more accurate representation of the dynamic conditions under which the disk operates. The project employs a conjugate heat transfer approach, which enables the simultaneous examination of various modes of heat transfer, including conduction within the disk, and convection between the disk and airflow.

Performance Difference between Radial and Directional Disk Brakes

For this project, two of the most common brake rotors will be compared, viz. radial and directional disk brake. Straight vane rotors, also known as radial or non-curved rotors, are widely used for general brake applications such as everyday street driving. They are lighter in weight as they require less material compared to curved rotors, but they have better cooling capabilities compared to solid rotors. However, when it comes to cooling and performance capability, there are other rotor vane designs that perform better.

On the other hand, curved vane rotors, also known as directional rotors, are predominantly used for motorsport or racing applications. They are typically heavier than straight vane rotors because more material is used for the curved vanes. This additional material gives curved vanes better thermal capacity, enabling them to withstand heavy brake applications better. They also provide better air circulation, which can improve the performance of the disc brake. However, the increased mass of curved vane rotors can potentially lead to higher wear and tear.

Brake Rotor CAD Models

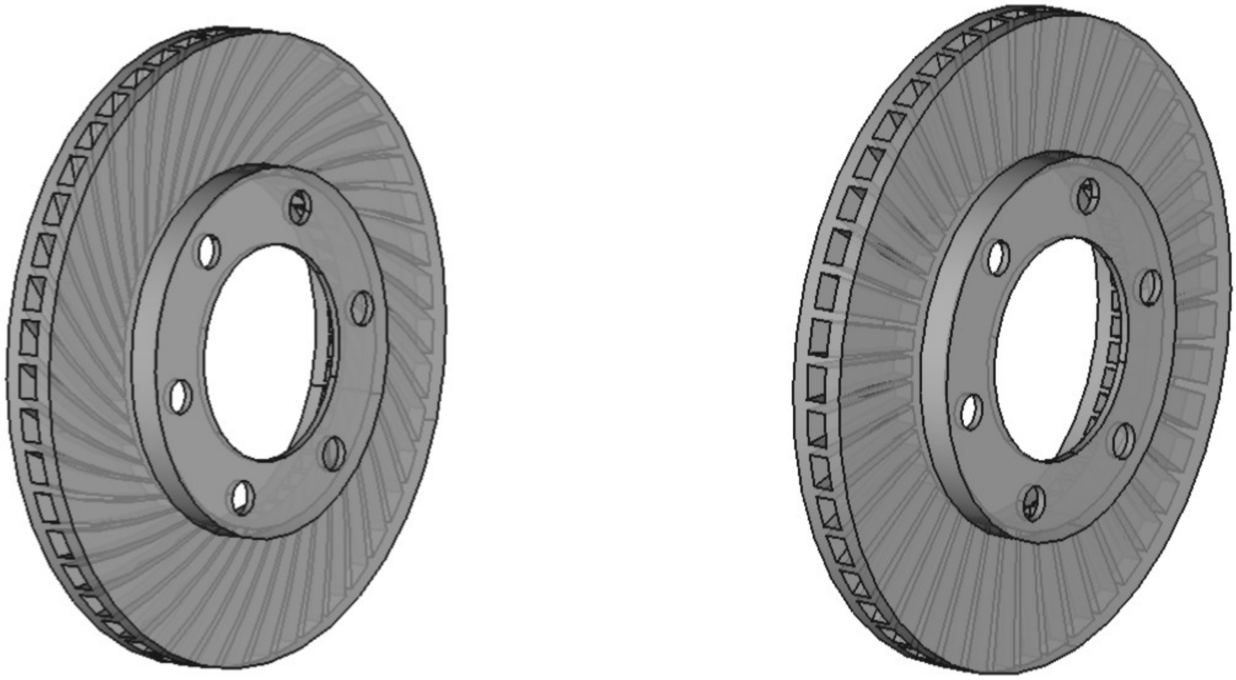

Figure 1: Directional disk brake rotor (Left); Radial disk brake rotor (Right)

Outer diameter [mm]	278
Inner diameter [mm]	155
Disk thickness [mm]	26
Number of Vanes	45

The disk specifications mentioned in the table above are kept as same for both the disk rotors. The modelling was done on *FreeCAD* software.

Simulation Domain and Setup

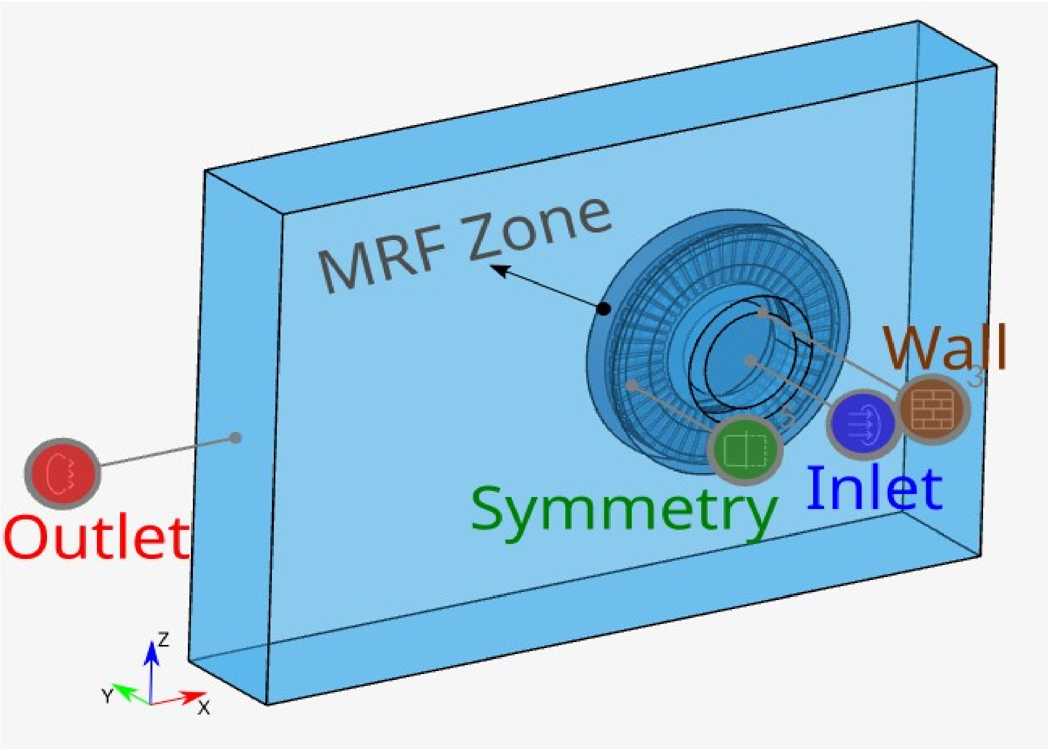

Figure 2: Simulation domain with boundary conditions

Domain length [mm] (*along x-axis*)	900
Domain width [mm] (*along y-axis*)	150
Domain height [mm] (*along z-axis*)	600
Fluid material	Air
Disk material	Steel
Inlet velocity [m/s] (*along y-axis*)	70
Disk rotational velocity [rad/s] (*about y-axis*)	230
Ambient temperature [ºC]	19.85
Time dependency	Steady-state
Turbulence model	k-ω SST
No. of volume cells (*Radial disk simulation*)	7,862,915
No. of volume cells (*Directional disk simulation*)	8,093,777

The entire simulation process is done on *Simscale* platform. The simulation domain size, initial conditions and boundary conditions were kept same for both CFD models of the disk rotors. The meshing parameters and inflation layer parameters were also kept same for both models. A MRF rotating zone was defined for both the rotors, with the same rotational velocity. The simulation is carried out in the steady-state condition since only the final temperature values and convective heat fluxes are the desired output for comparison. Under the constraint of limited computing resources, the mesh was kept at medium coarseness and the absolute tolerance for all scalar equations was set at 10^{-3}. Since the project is more qualitative in nature, therefore these setups would be sufficient to approximate the differing trends in the thermal dissipation of both the disks.

The simulation is designed by considering the disk brakes mounted on a car which is running at a speed of 70m/s (252 km/h). The braking action was done and then the car continues to cruise at the same speed of 70m/s. The heat produced due to braking at the given speed was modelled as a heat source in the simulation. Normally, the air enters from the intakes in the front bumper of the car and then channelized through a distributor into the disk rotor. A simplified model was made wherein a simple inlet pipe along the rotational axis was made and air is fed into it at 70m/s. The rotor geometry was also simplified by removing the holes for axle and bolts, since it is considered to be mounted on the car and air cannot pass through them.

The brake rotor dimensions, car speed and the corresponding heat source value were taken from [1].

Velocity Magnitude Contours

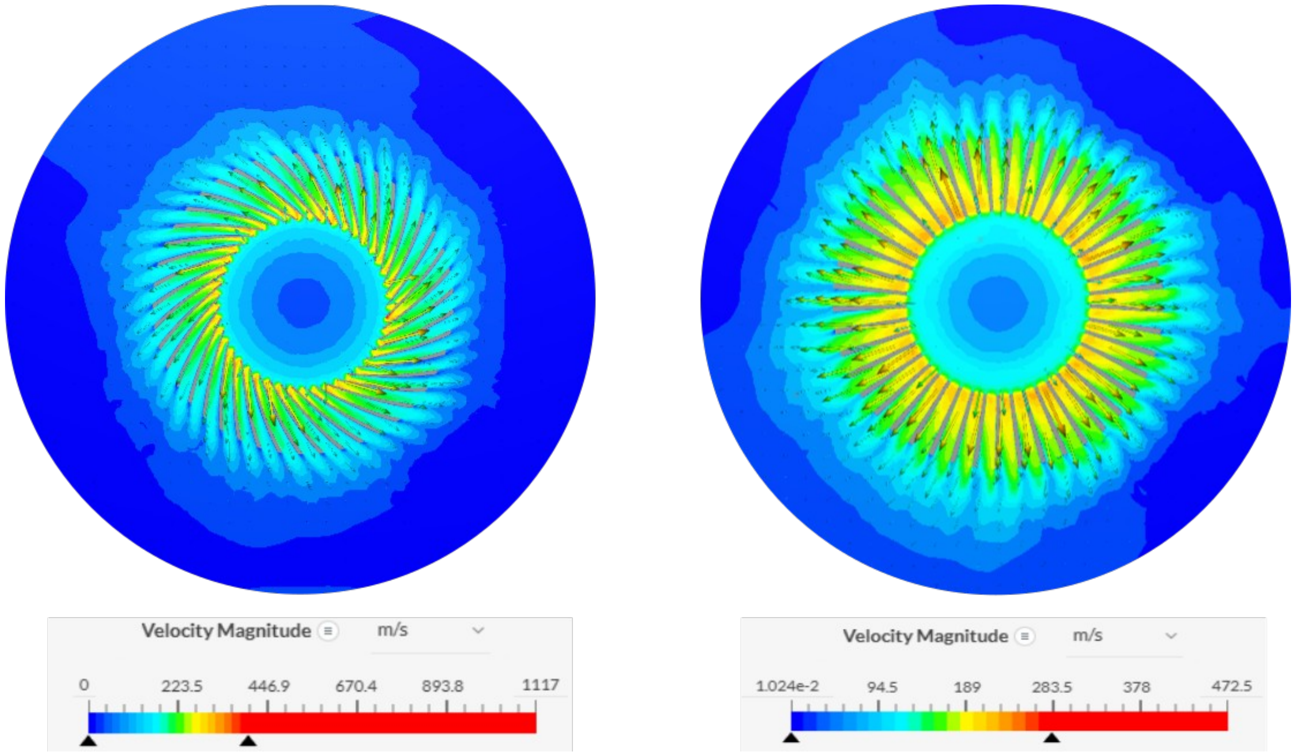

Figure 3: Velocity contour on a plane inside directional disk (Left) and radial disk (Right)

The air enters from the centre at 70m/s in both the disks. However, the detected top speed of air in the directional disk rotor is in excess of 1100m/s while it is 473m/s in the radial disk rotor. The overall flow velocity and flow-rate is larger in the directional disk rotor. Notice that the scales are adjusted for both contour figures in order to visualize the flow details.

Final Disk Temperatures and their Distributions

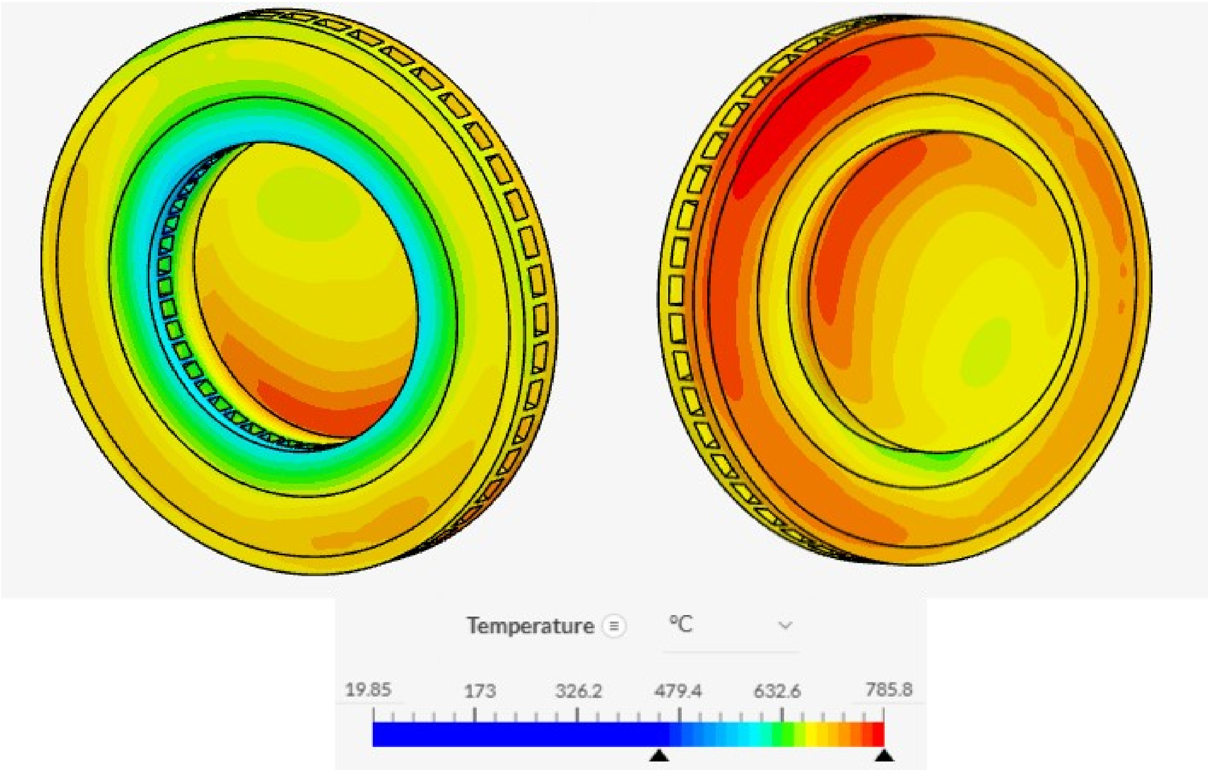

Figure 4: Temperature contour on radial disk rotor

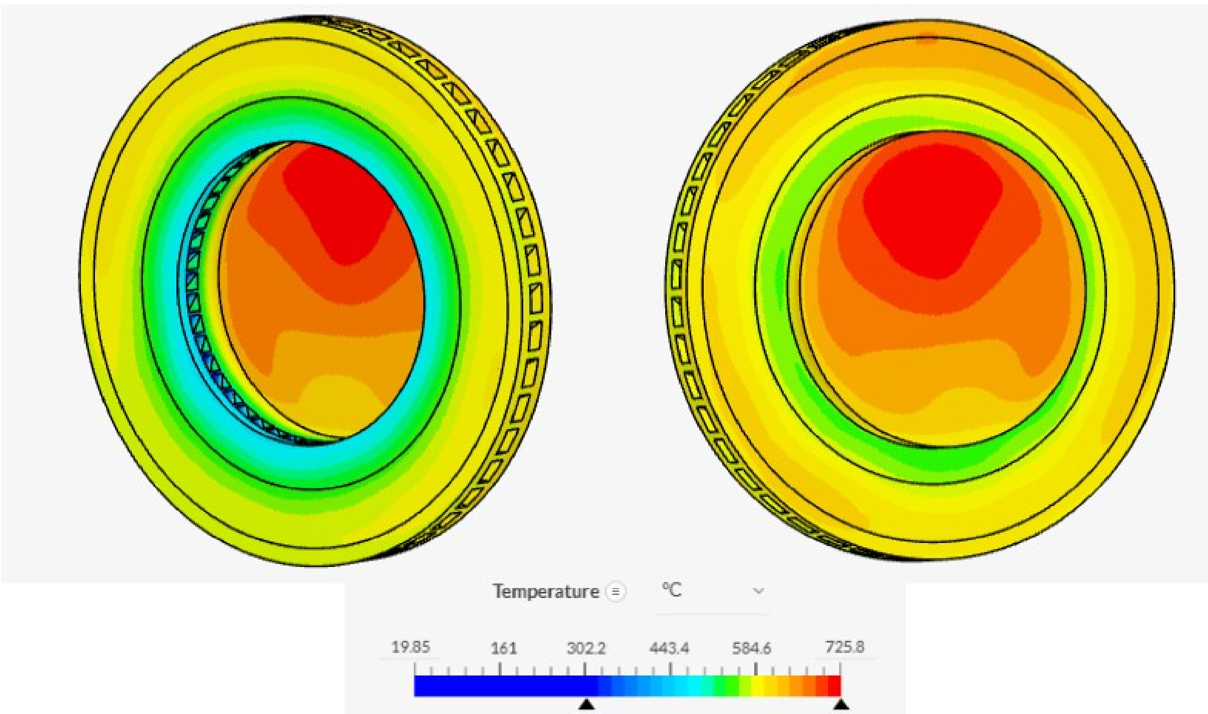

Figure 5: Temperature contour on directional disk rotor

	Directional disk brake	Radial disk brake
Maximum temperature [ºC]	725.8	785.8
Average temperature [ºC]	575	682.7
Minimum temperature [ºC]	306.3	450.8

Figures 4 and 5 shows the temperature contours on the disk rotors. The contour scales are adjusted according to the respective temperature range for both the disks. The temperature ranges are tabulated above for both the disks. The final temperature values indicates the superior thermal efficiency of the directional disk brake for high-speed operations.

Conclusion

In this project work, the radial disk rotor has a slightly larger volume which translates to a slightly more heat content in it. To be precise, the radial disk rotor has 0.8% higher heat content than the directional disk rotor. For the sake of argument, we can neglect this difference and consider them equal. This leads to a direct conclusion that the better heat dissipation in the directional disk rotor is a consequence of better airflow through it. The directional disk rotor essentially functions as a turbine which sucks the air through the centre and throws the air from the periphery. This results in a very high air flow-rate (as visualized in figure 3), and a consequent high convective heat transfer from the disk to the air at ambient temperature. When the vehicle is driven at very high speeds, the difference between the flow-rates of radial disk rotor and directional disk rotor becomes significantly high. Hence for very high operational speeds (and keeping all other factors same), the heat dissipation of directional rotors is much better than the radial rotors.

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