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An Overview of Cooling Solutions for Disc Brake Mechanism of Passenger Cars

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Abstract
The disc brake mechanism is an important part that ensures the necessary torque, receiveses the conversion of kinetic energy from vehicle speed into thermal energy during the braking operation, and increasing the temperature of the brake mechanism, which leads to a decrease in friction torque, reducing braking efficiency. To improve the efficiency of the disc brake mechanism, the cooling solutions for brake mechanisms with ventilated brake disc (VBD) are comprehensively analyzed in this study. The overall analysis results showed that the structural parameters of VBDs have a great influence on the cooling efficiency of the brake disc mechanism, especially when the vehicle brakes at high speed and the structural parameters of VBDs were optimized by the optimization algorithms such as GA, PSO, NSGA-II, Taguchi design of experiments, Integrated optimal design software package to improve the cooling efficiency of the disc brake mechanism. In addition, these general analysis results have provided researchers with directions for perfecting the cooling structure for VBDs.

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Keywords: Passenger cars, brake disk, cooling solution, VBD, cooling performance

1. Introduction

Brake cooling is of vital importance in high-speed cars due to the high demands placed on the braking systems during extreme driving conditions. The vehicles reach high speeds are faced with sudden and repeated manoeuvres, generating a significant amount of heat in the brakes. The research team proposed numerical models of the brake mechanism to analyze the structural and material influences on thermal efficiency, even cooling solutions [1, 2, 3, 4, 5]. The disc brake cooling characteristics proposed a specially developed spin rig to investigate their effect on cooling efficiency using numerical and experimental methods [6]. The mass flow of air going through ventilated brake discs (VBDs) and its dependency on various parameters, including the disc's temperature and rotational speed proposed to investigate the correlation between disc rotation rates and the amounts of air going through the disc vanes using an experimental method, and the results of the study have provided an experimental basis for improving the design of disc brake mechanisms [7]. Two brake disks with different straight ventilation hole shapes proposed to examine the cooling efficiency of a carbon-ceramic brake disk using numerical method based on the AMS (Auto-Motorsport) Fade mode [8]. A new concept of bidirectional VBD with an X-type lattice core proposed to improve the cooling performance of a disc brake system, and the transient and steady-state thermo-fluidic behaviors of the new brake disc were experimentally characterized and compared with a prevalent radial vane brake disc under identical conditions [9]. To improve the efficiency of VBD, structural optimization solutions have been carried out by scientists around the world. An optimized slotted vane geometry proposed to improve the heat dissipation performance of ventilated brake discs using NSGA-II algorithm and three structural parameters of slot width, slot inclination and number of vanes were selected as optimization variables, and the optimization objective was to maximize the mass flow rate and convection heat transfer coefficient [10]. The experimental method of the Taguchi design proposed to optimize the design of a VBD with radial vanes using three design parameters and the airflow and temperature distribution around the brake disc and tire using finite element method [11].

The optimum design of the brake disc with radial vanes was found based on the Taguchi design of experiments with taking into account nine design parameters [12]. The optimization of VBD rotor geometry for enhanced structural characteristic was found out based on Multi-objective optimization via Response surface methodology (RSM) [13].
A fully parameterized model for a ventilated brake rotor proposed to optimize structural parameters of VBD using using APDL (ANSYS Parametric Design Language) with 22 parameters uniquely defining the rotor geometry [14].
A nature-inspired optimal design for VBD was found out based on two nature-inspired optimization techniques, the genetic algorithm (GA) and particle swarm optimization (PSO) [15]. The optimal design of disc shapes was found out based on a multi-disciplinary integrated optimal design program [16]. The optimal design of the shape and pattern of holes and slits was found out based on an integrated optimal design software package to improve heat dissipation performance and structural stability [17]. Especially, a novel brake disc blade design with a unique geometry analyzed to find the optimal parameters of VBD using Fluid Topology Optimization [18]. The aim of this paper is to analyze an overview of the influence of VBD structure on thermal efficiency and the optimal structure parameters of VBD to enhance their cooling efficiency.

2. Aerodynamic - thermal model

The well-known Navier-Stokes equations for k-ε turbulent model [12] are solved to describe the velocity and pressure fields for the computational domain as
Continuity equation:

$$\rho \nabla.(u) = 0 \tag{1}$$

Momentum equation:

$$\rho(u.\nabla)u = \nabla.\left[-pI + (\mu + \mu_T)(\nabla u + (\nabla u)^T)\right] \tag{2}$$

Standard *k-ε* turbulence model equations

$$\rho(u.\nabla)k = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \mu_T\left[\nabla u : \left(\nabla u + (\nabla u)^T\right)\right] - \rho\varepsilon \tag{3}$$

$$\rho(u.\nabla)\varepsilon = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}\mu_T\left[\nabla u : \left(\nabla u + (\nabla u)^T\right)\right] - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{4}$$

where, ρ is the density; u is the velocity; p is the pressure; I is the identity matrix; μ is the dynamic viscosity; μ_t is the turbulent kinematic viscosity; k is the thermal conductivity; ε is the turbulent dissipation rate; T is the temperature; σ_t is the turbulent Prandtl numbers for ε; $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are constants.
The energy conservation equation is used to simulate the temperature distribution in the 3D space of the simulation domain:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u.\nabla T - \nabla.(k\nabla T) = Q \tag{5}$$

where, C_p is the specific heat; Q is the heat flow rate.
The high-speed rotation of the brake disc causes irregular airflow in the surrounding air, leading to heat transfer between the air and the brake disc surface. This process falls under forced convective heat transfer and follows Newton's law of cooling [19]:

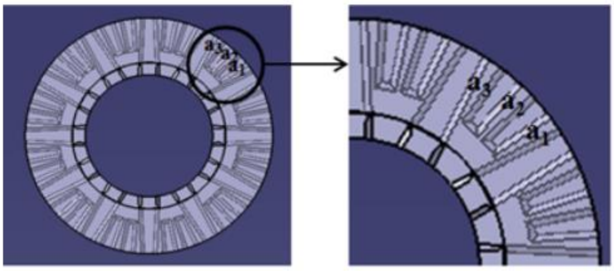
$$Q = Ah\,(T_w - T_f) \tag{6}$$

where, *A* is the solid surface area; T_w and T_f are wall temperature and fluid temperature, respectively; and h is the average convective heat transfer coefficient.

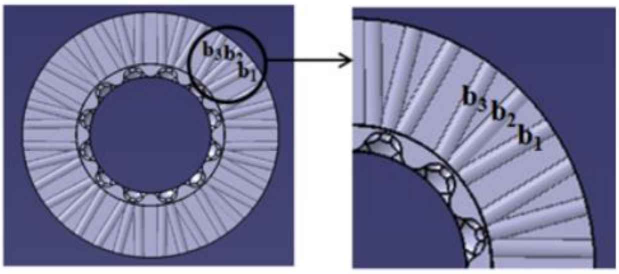
3. Cooling solutions for disc brake mechanism

3.1. Influence of the structures of ventilated brake disc (VBD) on thermal efficiency

Some research results mainly focus on structural analysis of VBDs to improve cooling efficiency. Two different shape models of A and B [8] were considered to find the best hole shape for air ventilation for a carbon ceramic disk. Two different models with ventilation holes [8] is shown in Fig.1.



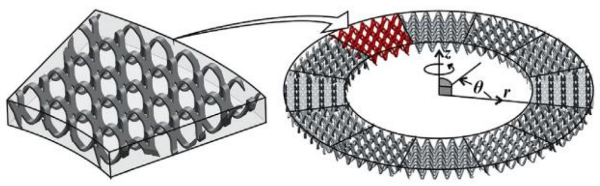
(a) Model A disk



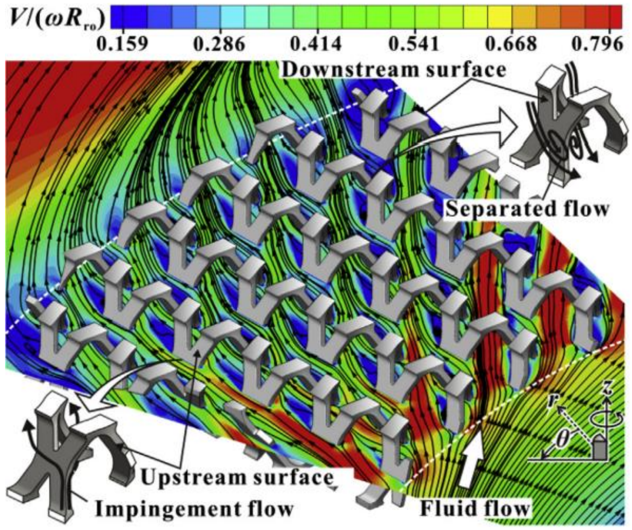
(b) Model B disk

Fig 1: Two different models with ventilation holes [8]

The obtained results have shown the mean temperature of the entire disk and the disk mid-plane increased 3.7^{0}C and 16.2^{0}C, respectively when a_2 hole length was increased from 94 mm to 128 mm due to the increased affined air stagnation in the disk in case of the model A disk and the disk mean temperatures were lower when using the holes with increased diameter over those of the base model in case of the model B disk.A new concept of bidirectional ventilated brake disc with an X-type lattice core [20] suggested to improve the cooling performance of a disc brake system and then, this research team developed the structure of X-type lattice core in VBD, twelve annular sector X-type lattice components [9] were integrated into the ventilated channel as a heat dissipation core. Its thermo-fluidic characteristics obtained both experimentally and numerically were presented along with direct comparisons with those of a radial vane brake disc and the preliminary X-type brake disc. The obtained results have shown the replacement of radial vanes by the X-type lattice reduced pumping capacity by approximately 40%, deteriorating therefore local heat transfer on the inner surface, the outer rim surface, the inner rim surface and the rubbing surface of the rubbing discs. Structures and results of X-type lattice in VBD [9] is shown in Fig.2.



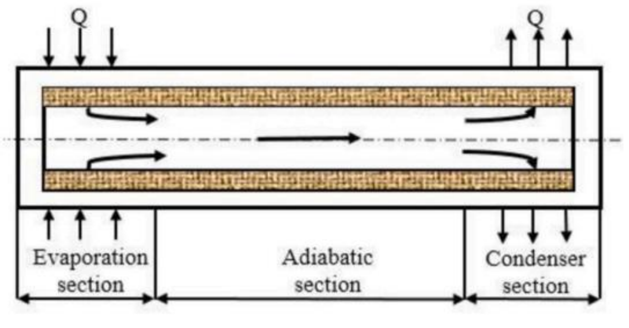
(a) Annular sector X-type lattice component



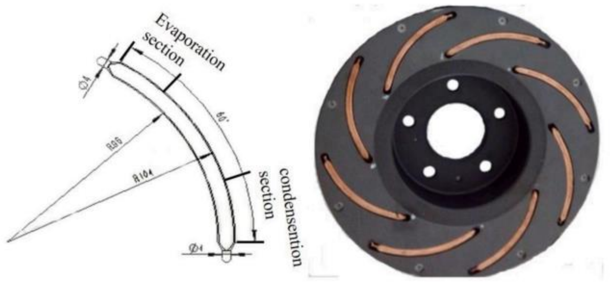
(b) Comparison of internal flow

Fig 2: Structures and results of X-type lattice in VBD [9]

The heat of high temperature zone [21] could be transferred to low temperature zone timely to achieve a better heat distribution on the surfaces of VBD using the inserting heat pipes on the outside surfaces of VBD. The obtained results have shown that the the maximum heat dissipation and the maximum temperature uniformity of VBD increased by 13.66% and 10.77% during repeated fifteen braking. Structure of VBD using heat pipes [21] is shown in Fig.3.



(a) Heat pipe

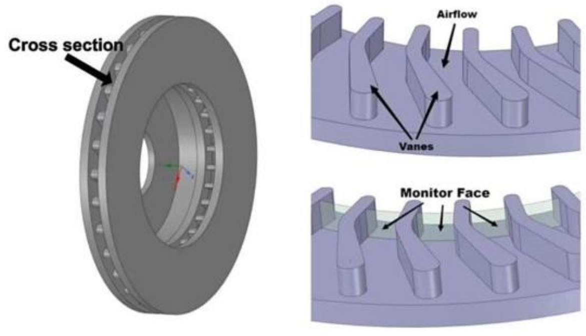


(b) Heat pipe ventilated brak

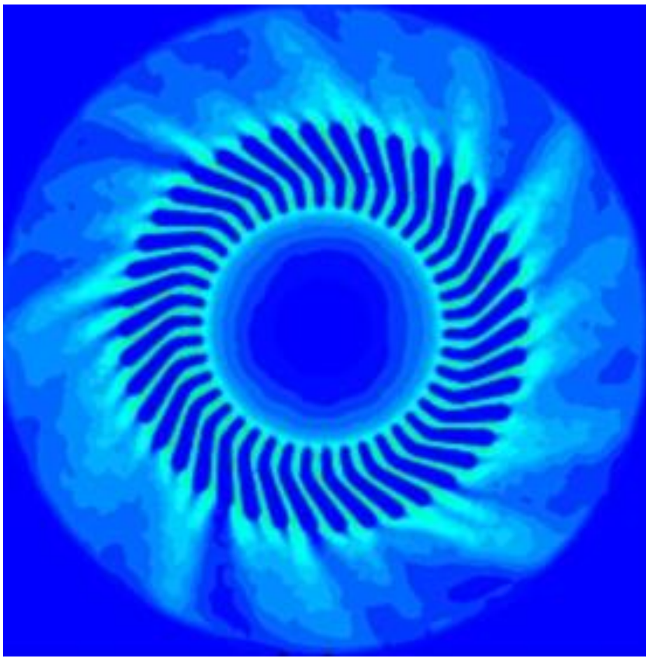
Fig 3: Structure of VBD using heat pipes [21]

3.2. Optimal structure parameters of VBDs

The structural parameters of VBDs are optimized by the optimization algorithms such as GA, PSO, NSGA-II, Taguchi design of experiments, Integrated optimal design software package to improve the cooling efficiency of the disc brake mechanism. The design of VBD with radial vanes using three designs are selected for optimization using Taguchi design of experiments. The structure and results of velocity distribution of the middle cross section is shown in Fig.4.



(a) Structures of VBD with radial vanes

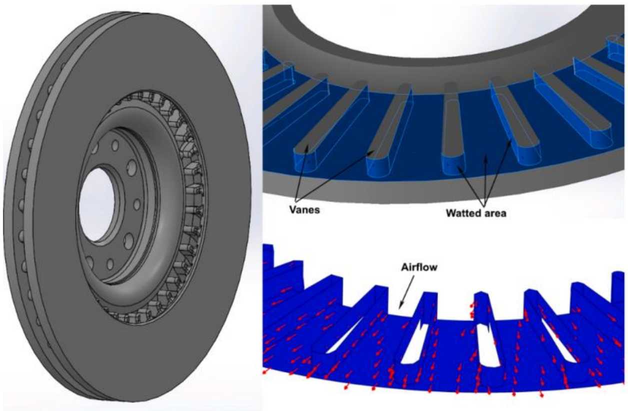


(b) Velocity distribution

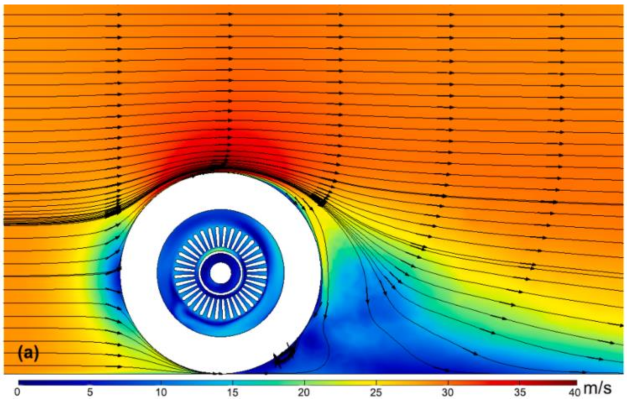
Fig 4: Structures and results of velocity distribution of the middle cross section [11]

The obtained optimal results [11] have shown that optimal structural parameters of VBD could be increased the ventilation gap from 10 to 14 mm, the bending angle of the blades from 29^0 to 37^0, and the cooling effect after emergency braking by 6.1% and 8.8%, respectively, when dissipating heat for 100 s at a driving speed of 60 km/h. The optimum design of VBD with radial vanes [12] found out using aguchi design of experiments. Taguchi L16 design and S/N ratios and means were used to evaluate the effects of nine parameters on the cooling performance of the disc from 400 ^{0}C to 100 ^{0}C. The obtained optimal results have shown that the ventilation gap width had the highest impact on the brake disc cooling and the cooling time of the disc decreased by

21% as the ventilation gap increases from 8 mm to 14 mm. Structures and result of velocity distribution in the cross sectional plane [12] is shown in Fig.5.



(a) Structure of VBD with split part



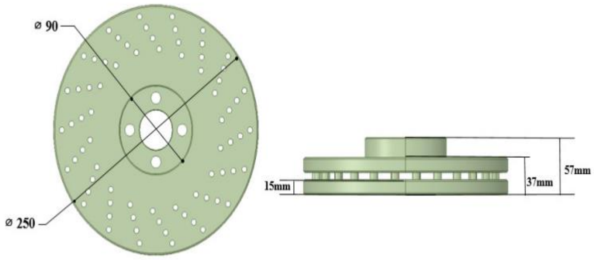
(b) Temperature distribution of disc

Fig 5: Structures and results of velocity distribution in the cross sectional plane [12]

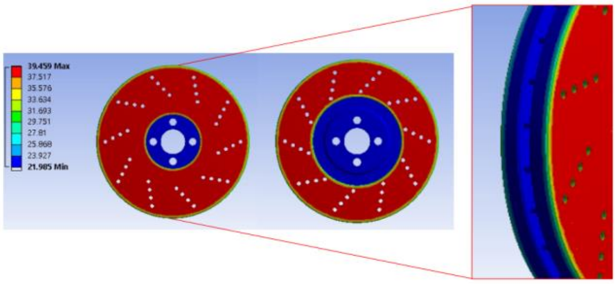
The design of the shape and pattern of holes and slits [17] was optimized using an integrated optimal design software package to the minimum concentrated stress and disc temperature. The obtained optimal results have shown that the stress of the optimal model decreased by 28.4% compared to the initial model (solid disc), from 64.04 MPa to 45.85 MPa; the temperature with the optimal model decreased by 6.57 ^{0}C, from 45.90 ^{0}C to 39.33 ^{0}C and the stress with optimal model was decreased by 23.2%, from 64.04 MPa to 49.20 MPa, and the temperature of optimal model was decreased by 10.77 ^{0}C, from 45.89 ^{0}C to 35.12 ^{0}C compared to the initial model. Structures and numerical analysis results of temperature distribution of disc [17] is shown in Fig.6.

4. Conclusions

In this study, an overview of the influence of VBD structure on thermal efficiency and the optimal structure parameters of VBD to enhance their cooling efficiency was analyzed based on research results in recent years. The overall analysis results showed that the structural parameters of VBDs have a great influence on the cooling efficiency of the brake disc mechanism, especially when the vehicle brakes at high speed and the structural parameters of VBDs were optimized by the optimization algorithms such as GA, PSO, NSGA-II, Taguchi design of experiments, Integrated optimal design software package to improve the cooling efficiency of the disc brake mechanism. In addition, these general analysis results will help the authors and researchers continue to develop research directions to perfect the structure of VBDs.



(a) Structure of VBD with holes and slits



(b) Temperature distribution of disc

Fig 6: Structures and numerical analysis results of temperature distribution of disc [17]

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