International Journal of Thermal Sciences 118 (2017) 355–366

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental and numerical study of turbulent flow and enhanced heat transfer by cross-drilled holes in a pin-finned brake disc

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ARTICLE INFO

Article history:
Received 18 October 2016
Received in revised form
23 April 2017
Accepted 24 April 2017

Keywords:
Ventilated brake disc
Pin-fin
Radial vane
Cross-drilled hole
Heat transfer enhancement

ABSTRACT

This numerical study presents a systematic comparison of the fluid flow and heat transfer characteristics between standard and cross-drilled ventilated brake discs incorporating pin-fins. To validate the numerical model, heat transfer measurement is performed for a commercially available standard brake disc. Within the representative operating range of 200–1000 rpm, results show that the introduction of cross-drilled holes on the rubbing discs enhances the overall cooling capacity of the pin-finned brake disc by 15–17%. As a result of axial pressure gradient, the low-momentum boundary-layer fluid near the rubbing surfaces is driven into the ventilated channel through the cross-drilled holes. Consequently, within radial spans of the cross-drilled holes, local heat transfer on the rubbing surfaces is evidently improved. In addition, the through-hole flow provides substantial heat removal from additional surface of the holes. However, the flow ejected from the cross-drilled holes blocks and interacts with the mainstream entered from the inlet of the ventilated channel, which ultimately reduces the effective flow area and increases resistance to the mainstream. Thus pumping capacity through the inlet of the ventilated channel decreases; and correspondingly, local heat transfer on other surfaces of the rubbing discs is slightly deteriorated. These mutually conflicting mechanisms are responsible for the superior overall cooling performance of the cross-drilled pin-finned brake disc.

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1. Introduction

Disc brakes as schematically illustrated in Fig. 1(a) are crucial security equipment in modern passenger vehicles and medium-sized trucks for deceleration. When a driver actuates the brake pedal, sliding friction forms between the brake disc and a pair of brake pads which independently rotate and remain stationary relative to the suspension system. Consequently, a large amount of kinetic and potential energy of the vehicle is transformed into thermal energy during high-load braking, which can lead to overheating of the brake disc. Many studies available in the open literature have shown that such overheating can result in deterioration of friction coefficient [1–3], severe wear of the rubbing surface [4], cracking of the rubbing disc induced by thermal stress [5–7] and thermal judder of the brake system as a result of non-uniform thermal deformation of the brake disc [8]. Consequently, effective and uniform cooling of the brake disc is crucial for disc brake systems.

To improve cooling performance, various ventilated brake discs have been devised and used in modern vehicles. These brake discs generally have a similar structure as those shown in Fig. 1(b). Aerodynamic and heat dissipation elements are sandwiched between two thick rubbing discs. Such brake discs work like centrifugal fans during rotation, sucking cooling air around the brake disc into the ventilated channel. Therefore, better cooling performance can generally be achieved due to the additional forced convection inside the ventilated channel and the enlarged heat transfer area relative to the limited convection near the rubbing surfaces of a solid brake disc [9]. Among the ventilated brake discs with radial vanes, curved vanes and pin-fins, the application of curved vane brake discs are limited since this type of brake disc is unidirectional. In contrast, radial vane and pin-finned brake discs are bidirectional; and the same brake disc can be mounted to any tire of a vehicle.

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.04.024
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Nomenclature

A	heat transfer area (m^2)
d_h	diameter of the circular cross-drilled holes (m)
d_p	diameter of the circular pin-fins (m)
h	local heat transfer coefficient ($W/(m^2K)$)
h_e	local effective heat transfer coefficient defined in Eq. (4) ($W/(m^2K)$)
$h_{overall}$	overall heat transfer coefficient defined in Eq. (3) ($W/(m^2K)$)
H_{h1}, H_{h2}	axial dimensions of the hub of the brake disc (m)
H_p	height of the pin-fins (m)
k	thermal conductivity of air (W/(mK))
L_p	length of the pin-fins (m)
N	rotational speed of the brake disc (rpm)
Nu	local Nusselt number
Nu_e	local effective Nusselt number defined in Eq. (5)
$Nu_{overall}$	overall Nusselt number defined in Eq. (2)
p	pressure (Pa)
q''	heat flux imposed by each heating pad (W/m^2)
r	radial coordinate (m)
r_{p1}, r_{p2}	round radii of the pin-fins (m)
Re	rotational Reynolds number defined in Eq. (1)
$R_{h1}-R_{h4}$	radial locations of the cross-drilled holes (m)
R_{hb1}, R_{hb2}	radial dimensions of the hub of the brake disc (m)
R_i, R_o	inner and outer radii of the inboard disc (m)
$R_{p1}-R_{p4}$	radial locations of the pin-fins (m)
t_r	thickness of the rubbing disc (m)
T	local wall temperature (°C)
T_a	reference air temperature (°C)
T_{rs}	local temperature on the inboard rubbing surface (°C)
$T_{rs,\ m}$	area-averaged rubbing surface temperature (°C)
V	relative velocity magnitude (m/s)
W_p	width of the pin-fins (m)
z	axial coordinate (m)

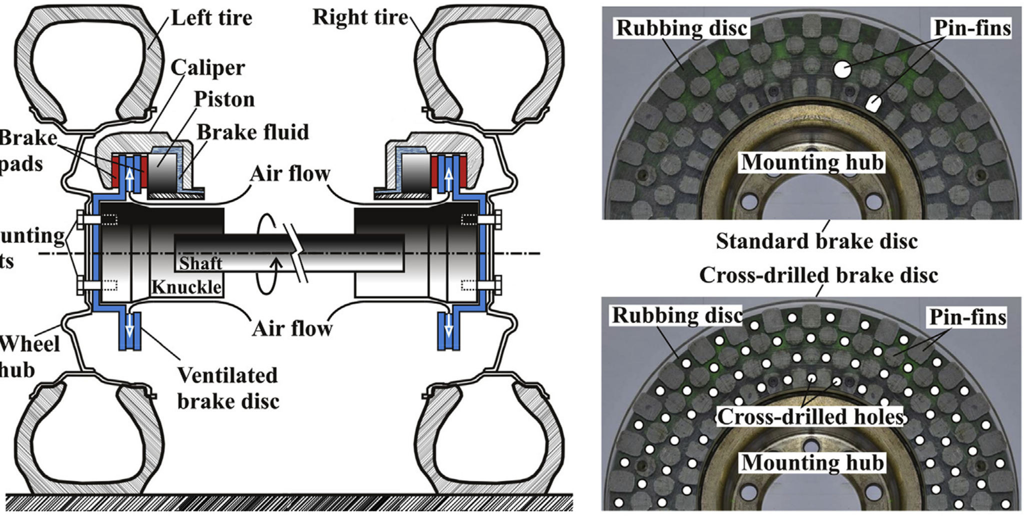
Greek symbols

ε	emissivity of the matt black paint
η	contribution of separate mechanism to overall heat transfer enhancement
θ	azimuth coordinate (rad)
θ_0	periodic angle of the brake disc (rad)
μ	dynamic viscosity of air (Pa·s)
ρ	density of air (kg/m^3)
σ	Stefan-Boltzmann constant ($W/(m^2K^4)$)
ω	angular velocity magnitude (rad/s)

Although the radial vane brake disc generally has better overall cooling performance than the pin-finned brake disc, the latter such as the one as shown in Fig. 1(b) exhibits better thermal uniformity inside the brake disc due to more uniform distribution of the core elements along both the radial and circumferential directions, which helps to prevent thermal cracking [10,11]. Therefore, both types of brake discs are widely used in modern vehicles [12]. The present study focuses on the pin-finned brake discs.

Commercially available bidirectional ventilated brake discs may be classified into standard and cross-drilled brake discs as shown in Fig. 1(b) [12]. Since 1960s [13], numerous analytical, numerical and experimental studies have been conducted to characterize the thermo-fluidic characteristics of the standard brake disc. In contrast, investigation into the cross-drilled brake disc is limited.

For the standard pin-finned brake disc, Barigozzi et al. [14,15] measured mean velocity and turbulence intensity distributions on several cylindrical cross-sections at the exit of the ventilated channel. The brake disc considered by these authors has diamond and teardrop shaped pin-fins. Jet-like exit flows were reported; and the non-dimensional velocity and temperature distributions were independent of the rotational speed of the brake disc. Wallis et al. [16] investigated numerically the flow characteristics inside a ventilated brake disc with diamond and teardrop shaped pin-fins. It was reported that a low-momentum separated region exists downstream each pin-fin. Manohar Reddy et al. [10] compared numerically the flow and heat transfer characteristics of two brake discs separately with diamond and circular pin-fins. It was found that the former exhibited better cooling performance although the



(a) (b)

Fig. 1. Illustration of a ventilated disc brake system: (a) the components and working principle; (b) standard and cross-drilled ventilated brake discs with pin-fin elements.

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