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Turbulent flow characteristics and heat transfer enhancement in a square channel with various crescent ribs on one wall

Gongnan Xie [a,*], Xueting Liu [b], Hongbin Yan [a,*], Jiang Qin [c,*]

[a] *Department of Mechanical and Power Engineering, School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, China*
[b] *School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, China*
[c] *School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

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A B S T R A C T

This numerical study reports on fluid flow and heat transfer characteristics in a cooling channel with various crescent ribs mounted on one wall. Based on available experimental data, a series of simulations with various turbulence models are conducted to find the best numerical model. Three kinds of ribs, i.e., the straight rib, the crescent rib concave to the stream-wise direction, the crescent rib convex to the stream-wise direction, are considered to improve thermal performance of the cooling channel. The studied Reynolds number varies from 8000 to 24,000. Mechanisms underlying the enhanced heat transfer by ribs are clarified. It is found that the crescent ribs evidently enhance local heat transfer on the endwall downstream the ribs by generating longitudinal vortices, which intensify flow mixing. Such vortices also increase the turbulent kinetic energy and reduce thickness of the boundary layer, which lowers local temperature nearby the target surface. Numerical results show that the cases with crescent ribs significantly outperform the case with straight ribs with respect to heat transfer performance. The crescent ribbed channels provide a 21–41% higher normalized average Nusselt number relative the straight ribbed channel, while inevitably lead to a 15–80% higher pressure drop. Overall, the case with crescent ribs concave to the stream-wise direction provides the best thermal performance.

1. Introduction

There are a variety of techniques used to enhance convective heat transfer in channels, such as pin fins, dimples, protrusions, grooves, swirl chambers and rib turbulators [1–6]. Ribs protruded from the endwall have been commonly used since the introduction of ribs can interrupt fluid flow, make the thermal boundary layer redevelop, intensify flow mixing by inducing vortices and enlarge heat transfer area. As revealed in [7], internal rib turbulators can enhance overall heat transfer effectiveness on external surface of the vane by up to 50% relative to the situation without ribs.

Numerous experimental and numerical investigations have been conducted to explore the effects of various parameters such as shape and configuration of ribs as well as shape of cooling passages on fluid flow and heat transfer [8–10]. According to [8,11–14], both THE geometric parameters of channels and working conditions have significant effects on the thermal performance. Typically, it was reported in [8,13] that the shape of ribs has a more evident effect on pressure drop than that on heat transfer.

Lots of studies focus on the thermal performance in the channel roughened with various shaped ribs. Stephens et al. [15] firstly performed computations to investigate the three-dimensional flow field and heat transfer performance in a rectangular channel roughened with five equally-spaced 90° square ribs on the bottom wall. Flow separation takes place before the rib and after the rib as well as on top of the ribs. Leonardi et al. [16] carried out direct numerical simulations for a fully turbulent flow in a rectangular cavity with square ribs mounted on the bottom surface. For the ratio of distance between the adjacent ribs to the height of rib is more than 7, recirculation zones immediately occur upstream and downstream of each rib while mean streamlines and spatial distributions of the skin frictional drag indicate that each rib is virtually isolated. Murata and Mochizuki [17] performed large eddy simulation to investigate the effects of transverse ribs on turbulence by changing the rotation number and the aspect ratio. According to the study, the heat transfer enhancement caused by the rotation is larger than that by the higher aspect ratios for the secondary flow induced by the intensified Coriolis. Han et al. [18] conducted experiments to investigate the effects of rib shape, angle of attack and pitch to height ration on the thermal performance in rib-roughened surface. According to the research, the rib

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* Corresponding authors.
E-mail addresses: xgn@nwpu.edu.cn (G. Xie), hbyan@nwpu.edu.cn (H. Yan).

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Nomenclature

b	depth of the crescent rib concave or convex to the streamwise direction (m)
D_h	hydraulic diameter of the channel (m)
e	width of the rib (m)
f	Fanning friction factor defined in Eq. (4)
f_0	Fanning friction factor in smooth channel defined in Eq. (5)
h	height of the rib (m)
H	height of the square channel (m)
K	turbulent kinetic energy (m^2/s^2)
L	length of middle part in the channel (m)
Nu	average Nusselt number
Nu_0	Nusselt number for fully developed flow in a smooth channel defined in Eq. (3)
$Nu(i)$	local Nusselt number defined in Eq. (2)
O_1, O_2	location of the center of a circle
Δp	pressure drop across the test section (Pa)
P	pitch of ribs (m)
Pr	Prandtl number
q	heat flux (W/m^2)
R	radial dimensions of the crescent ribs (m)
Re	Reynolds number defined in Eq. (1)
T	local temperature (K)
T_f	mass-averaged temperature in the middle part of the channel (K)
T_{in}	fluid temperature at the inlet of the cooling channel (K)
u	fluid velocity (m/s)
W	width of the square channel (m)
x, y, z	Cartesian coordinate components (m)
X	distance from an arbitrary position to the front rib (m)
y^+	dimensionless wall distance

Greek symbols

ρ	density of air (kg/m^3)
μ	dynamic viscosity of air (Pa·s)
λ	fluid thermal conductivity (W/(m K))

cross-section has a marked effect on the friction factor and a very modest effect on the heat transfer. Laterally, Han and Park [19] studied the combined heat transfer performance in the channels mounted with inclined ribs. Herein, angled ribs (the angle-of-attack is 30–45°) provide about 30% higher heat transfer performance than the transverse ribs does for a constant pumping power. As reported by Yang et al. [20], the increase in heat transfer is accompanied by an increase in friction factor ratio in a channel with angled ribs. During the development of investigations upon the ribs, there are several types of rib occur. Jia et al. [21] numerically investigated the heat transfer and fluid flow phenomena in straight square ducts with V-shaped ribs. It was found that the V-shaped ribs pointing downstream induce a higher friction factor than the V-shaped ribs pointing upstream does. Tanda [22] used liquid crystal thermography to obtain detailed distributions of the heat transfer coefficient in the channels with ribs having rectangular or square sections deployed transverse to the main direction of flow or V-shaped with an angle of 45 or 60° relative to flow direction. In this study, the effect of continuous and broken ribs was considered. Taking pressure drop into account, transverse broken ribs with p/e = 4 and 13.3 have the best thermal performance, while transverse continuous ribs provide a little heat transfer augmentation or even a reduction. Bergmann and Fiebig [23] compared the local and global turbulent heat transfer in square channel with roughness elements in the form of V-shaped broken ribs attached at two opposite walls. The results showed a symmetric behavior of flow structure and Nusselt number distribution to the middle of the height and span-wise direction. Peng et al. [24] experimentally and numerically investigated convective heat transfer in a channel with straight ribs and V-shaped ribs. Compared with a flat wall without ribs, both the straight ribs and V-shaped ribs enhance heat transfer at the cost of higher pressure drop. Results showed that overall thermal performance of the channel with V-shaped ribs is superior to that with the straight ribs. Ahn [25] made a comparison of thermo-hydraulic performance in rectangular ducts with five types of ribs. He concluded that the triangular rib has a substantial superiority regarding heat transfer capacity to the other ones. The square rib provides the highest friction factor. Wang et al. [26] conducted numerical simulations to predict single-phase turbulent forced convection flow in a channel with triangular ribs, asymmetric arc ribs and compound ribs within the Reynolds number range of 20,000–60,000. It was found that the compound ribs can improve heat transfer performance and decrease pressure drop concurrently. Zheng et al. [27] installed six types of ribs on the bottom wall of a square channel to improve heat transfer in the leeside of the ribs. They reported that ribs with an inclined leeside structure corresponding to an inclination angle of 160° yield 4.6–6.4% higher heat transfer than rectangular ribs. Furthermore, the rib with an inclined leeside structure corresponding to an inclination angle of 160° exhibits the highest pressure drop among the six types of ribs. Wang and Sunden [28] carried out experimental studies to investigate heat transfer in a square duct roughened by ribs having different shapes. They showed that the trapezoidal ribs with decreasing height in the flow direction provide the highest heat transfer enhancement factor. As reported by Yang et al. [20], the increase in heat transfer is accompanied by an increase in friction factor ratio in a channel with angled ribs. It is known from the literatures [29,30] that the truncation of ribs can reduce pressure drop penalty but slightly deteriorates heat transfer. Saini et al. [31] carried out an experimental study for heat transfer enhancement in an air duct roughened by arc-shaped ribs. It provides a superiority of 3.8 and 1.75 times in Nusselt number and friction factor relative to the smooth channel. An optimal rib structure has not yet been found.

In view of the above, the shape of ribs has an important effect on fluid flow and heat transfer in the channel. In this paper, a new type of rib called “crescent rib” shown in Fig. 1(c and d) is designed based on the straight rib and pin fin. It is expected that the crescent rib can generate longitudinal vortices, which are capable to intensify the disruption of thermal boundary layer to enhance heat transfer in the channel. Specific flow field and heat transfer characteristics in the channel mounted with crescent ribs are investigated in the present study.

2. Numerical details

2.1. Computational domain and boundary conditions

The computational domain consisting of the first part, the middle part and the last part is schematically shown in Fig. 1(a). The smooth first part and last part have a length of 750 mm and 250