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Effect of rib orientation on thermal and fluid-flow features in a two-pass parallelogram channel with abrupt entrance

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ABSTRACT

Detailed secondary flow patterns, Nusselt number (*Nu*) distributions, Fanning friction factor (*f*), and thermal performance factor (TPF) are compared between three different rib orientations (45-deg, −45-deg, and 90-deg) in a stationary two-pass parallelogram channel with an asymmetrically and suddenly contracted inlet condition. Velocity and temperature measurements are performed with Particle Image Velocimetry (PIV) and Infrared Thermometry (IT). Temperature and pressure drop measurements are conducted under Reynolds number (*Re*) ranging from 5000 to 20,000, while the velocity measurements are carried out at fixed $Re = 10{,}000$. A cross-sectional equal length, 45.5 mm, of adjacent sides is selected and two pairs of opposite angles are 45-deg and 135-deg. The rib-height to channel-height ratio and rib pitch-to-height ratio are 0.1 and 10, respectively. It is found that the combined effect of inlet condition and rib orientation extends to whole parallelogram channel rather than the first passage only. Among the rib orientations investigated, the 45-deg ribs strengthen the effects of parallelogram slant sidewalls and entrance and further widen the *Nu* difference between top and bottom walls. In contrast, the other two rib configurations, 90-deg ribs especially, weaken these effects and narrow the corresponding differences. Based on the ability to elevate the surface-averaged $\overline{Nu_0}/Nu_\infty$ ratio, the orders (45-deg, −45-deg, 90-deg) and (90-deg, 45-deg, −45-deg) respectively for present top and bottom walls are significantly distinct from those in square and rectangular channels. The variations of channel-averaged $\overline{Nu_0}/Nu_\infty$ and $\overline{f_0}/f_\infty$ with the associated TPF values against *Re* are plotted and compared with previous results obtained from literature. Overall speaking, three tested angled ribs all provide the TPF values above than unity; however, only the TPF values in 45-deg case are always higher than those in corresponding smooth parallelogram channel (ASI case). Divided by the TPF values in ASI case, the normalized TPF values are respectively 1.09–1.04, 1.07–0.87, and 0.83–0.99 for 45-deg, 90-deg, −45-deg ribbed cases. It is thus important to take the entrance effect into account when applying the angled ribs in a two-pass parallelogram channel.

1. Introduction

For turbine blade cooling, the serpentine internal coolant channel is one of the most frequently employed mechanism and thus widely investigated by many research groups. The configurations of the internal coolant channel such as channel cross-sectional geometry and aspect ratio, the shape of the turn, and the divider thickness are found to remarkably affect the thermal fluid behavior. Rib turbulators, on the other hand, are applied to the internal coolant channel to enhance thermal performance. Turbulent heat transfer in a ribbed channel with a 180-deg turn is influenced by inlet flow condition; rib-generated cross-sectional secondary flow, recirculating flows, and flow reattachments; turn-induced Dean and corner vortices, flow impingements, and separating bubble; and mean flow shear-induced high turbulence intensity levels.

Up to the present, numerous studies have paid their attention to examining the turbulent heat transfer performances between different rib configurations, such as rib orientation [1–15], rib pitch [1,13,14,16,17], rib blockage ratio [18], and rib geometry (detached, perforated, truncated, staggered, V-Shape, W-Shape, scale, dimple, pin-fin, etc.), in the channels with square, rectangular, circular, triangular, and trapezoidal cross-sections. Note that all the cited references involving with rotational condition were also performed under stationary condition ($Ro = 0$). Those results with $Ro = 0$ are thus gathered in the present work for discussion and

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Nomenclature

English symbols

A	cross-sectional area (m^2)
AR	aspect ratio $= W_1/(B/\sin 45°) = W_2/(B/\sin 45°)$ for the present parallelogram channel
B	channel height (m)
Bi	Biot number $= hD_H/k_s$
C_p	specific heat of fluid (J kg^{-1} K^{-1})
D_H	hydraulic diameter $= 4A/P$ (m)
f_0	fanning friction factor for each channel wall $= [\Delta P/(0.5\rho U_b^2)]/(4L/D_H)$
f_∞	Blasius equation for turbulent flow $= 0.079Re^{-0.25}$
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	rib height (m)
k_f	thermal conductivity of fluid (W m^{-1} K^{-1})
k_s	thermal conductivity of stainless foil (W m^{-1} K^{-1})
L	channel length (m)
Δl	laser light sheet thickness (m)
N	rib index
$\overline{Nu}$	averaged Nusselt number
Nu	local Nusselt number $= hD_H/k_f$
Nu_∞	Nusselt number value evaluated from Dittus-Boelter correlation $= 0.023Re^{0.8}Pr^{0.4}$
P	perimeter of cross-section (m)
Pi	rib pitch (m)
Pr	Prandtl number $= \mu C_p/k_f$
P_T	total input heat flux provided by power supply (W m^{-2})
ΔP	pressure drop across scanned section (Nm^{-2})
q_f	convective heat flux (W m^{-2})
q_{loss}	heat loss to the environment (W m^{-2})
Re	Reynolds number $= \rho U_b D_H/\mu$
Ro	rotation number $= \Omega D_H/U_b$
S	traveling distance along each section (m)
T_b	bulk fluid temperature (K)
T_w	wall temperature (K)
T_∞	ambient temperature (K)
TPF	thermal performance factor $= (\overline{Nu}_0/Nu_\infty)/(\bar{f}_0/f_\infty)^{1/3}$
Δt	shutter of CCD camera (s)
U_b	bulk flow velocity (m s^{-1})
U	streamwise mean velocity (m s^{-1})
V	transverse mean velocity (m s^{-1})
$\lvert V\rvert$	velocity magnitude traveling through the laser light sheet (m s^{-1})
W	spanwise mean velocity (m s^{-1})
W_1	width of first-pass duct (m)
W_2	width of second-pass duct (m)
W_d	divider thickness (m)
W_r	rib width (m)
X	streamwise coordinate (m)
X*	normalized streamwise coordinate $= X/D_H$
Y	transverse coordinate (m)
Y*	normalized transverse coordinate $= Y/B$
Z	spanwise coordinate (m)
Z*, Z**	normalized spanwise coordinate for all Y* (i) X < 0, $Z^{**} = Z/[(W_1 + W_2 + W_d)/2]$ (in the turn) (ii) X ≥ 0, Z < 0, $Z^* = [Z + (W_d/2)]/W_1$ (in the 1 st pass) (iii) X ≥ 0, Z > 0, $Z^* = [Z - (W_d/2)]/W_2$ (in the 2nd pass)

Greek symbols

α	angle of rib (deg)
ε	coefficient of heat flux non-uniformity
ξ	ratio of the out-of-plane displacement to the laser sheet thickness $= \lvert V\rvert\Delta t/\Delta l$
ρ	fluid density (kg m^{-3})
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})
Ω	rotational speed of test duct (rad s^{-1})
Ω_x	X component of the rotation vector (s^{-1})
Ω_Z	Z component of the rotation vector (s^{-1})

Subscripts

1	first passage
2	second passage
t	turning region
s	refer to smooth situation
0	refer to non-rotating situation
∞	refer to the smooth circular straight duct under fully developed condition

comparison. After researching 12 different turbulators in a square channel with Laser-Doppler Velocimetry (LDV) and transient liquid crystal thermography (TLCT), Liou et al. [19] concluded that among flow dynamics variables examined the direction and strength of the secondary flow with respect to the channel wall were the dominant ones, followed by the convective mean velocity. The turbulent kinetic energy distribution was found to be less correlated with the Nusselt number ratio distribution. Moreover, the above studies all suggested that heat transfer characteristics generally varied from one rib configuration to another due to different combination of the induced longitudinal and spanwise vortices.

Han et al. [1] used thermocouples and pressure taps to examine a ribbed square duct with α = 30-deg, 45-deg, 60-deg, and 90-deg. The experiments were conducted under two entrance conditions: a fully developed inlet and a symmetric sudden contraction inlet. Their results showed that the best thermal performance under a constant pumping power was achieved at both α = 30-deg and 45-deg for both entrance conditions. Compared with the case of α = 90-deg, the thermal performance for α = 30-deg and 45-deg was 30–50% higher. Han and Park [2] further explored the effect of rib angle in three different aspect ratio rectangular channels under symmetric sudden contraction inlet. They reported that the best thermal performances still occurred in the cases of α = 30-deg and 45-deg for different aspect ratios. However, the percentage of thermal performance augmentation was found to decrease from 30% to 5% when the aspect ratio varied from 1 to 2 and 4. Al-Hadhrami and Han [11] conducted an experimental study to investigate the effect of various 45-deg angled rib arrangements on the Nusselt number ratio in a fully developed two-pass square channel. They concluded that there was no difference between positive and negative rib angle for regional *Nu* ratio. Moreover, both +45-deg and −45-deg parallel rib arrangements were found to provide higher heat transfer enhancement compared with the cross-type 45-deg rib arrangement.

Using the naphthalene sublimation technique, Zhao and Tao [7] investigated mass transfer in a ribbed two-pass square channel under uniform inlet condition. Five types of angled rib, i.e. α = ±45-deg, ±60-deg, and 90-deg, were attached on two opposite walls in both two passages as well as turn region. They found that for α = 60-deg the overall average Sherwood number of the entire rib-roughened wall was the highest and the others were in the order of α = 45 > −60 > −45 and 90 degrees. Kiml et al. [8] experimentally studied the effect of rib angle for α from 45-deg to 90-deg with an interval of 15-deg in a fully developed rectangular duct