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Research Paper

Heat transfer study in a rotating ribbed two-pass channel with engine-similar cross section at high rotation number

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HIGHLIGHTS

- Rib effects in a rotating channel with engine-similar cross section are studied.
- Three channel orientations are discussed with up to $Ro_1 = 1.88$ and $Ro_2 = 0.972$.
- The most remarkable effect of Ro on Nu/Nu_s is on trailing side of inlet pass.
- Heat transfer is enhanced by rotation more severely at a larger rotation number.
- Channel orientation influences the heat transfer more significantly at a larger Ro.

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ABSTRACT

The heat transfer in a rotating ribbed two-pass channel with engine-similar cross section has been experimentally investigated in the current study. The Reynolds number ranges from 10,000 to 50,000 for the inlet pass and 12,000 to 62,000 for outlet pass. The highest rotation number is 1.88 for the inlet pass and 0.972 for outlet pass. For channels, the leading and trailing sides are roughed with ribs (P/e = 9.8) placed at 90° angle to the mainstream flow, and three channel orientations are considered (0°, −22.5°, and −45°). Results show that placing ribs strengthen heat transfer for both stationary and rotating cases, and the ribs weaken the entrance effect. In the inlet pass, the most remarkable effect of Ro on Nu/Nu_s is obtained on the trailing side, and a critical Ro is formed on leading and outer side. The heat transfer is enhanced by the rotation more severely at a larger Ro ($Ro_1 > 1$, $Ro_2 > 0.5$). Moreover, the $\beta = 0°$ channel experiences the strongest heat transfer enhanced by rotation with the least in the $\beta = -45°$ channel. At last, the average Nu/Nu_s correlations considering Ro and Re are developed, a relatively pleasant accuracy ($\leqslant 10\%$) has achieved.

1. Introduction

The development of cooling technologies has always been advanced by the increasing demands of high efficiencies of gas turbine as the high turbine inlet temperature (which defines the efficiencies of the engine) will create thermal stresses on blades. In turbine blades, external cooling and internal cooling methods are applied to ensure they are operating in reasonable temperature range. Internal cooling is achieved by circulating compressed air in multi-pass flow channels inside the blade structure. To increase the heat transfer within the internal cooling channels, the internal surface is usually roughened by angled ribs to trip the boundary layer and increase turbulence. As the turbine blades rotate the inertia force, rotation induced Coriolis and centrifugal buoyancy force will cause different heat transfer behaviors on the leading and trailing surfaces. Furthermore, the cross section and channel orientation of the internal cooling channels vary from the leading edge to the trailing edge. These geometrical factors can also influence the heat transfer in channels. Over the past several decades, a vast amount of studies on internal cooling of turbine blades have been investigated by researchers, and many of these works have comprehensively reviewed by Han [1–3].

Earlier studies on cooling channels were primarily based on stationary models. Han and Zhang [4] studied the effect of rib-angle orientation on the local heat/mass transfer distribution in a stationary three-pass ribbed channel. It was observed that the rib angle, rib orientation, and the sharp 180° turn significantly affect

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Nomenclature

English symbols

A	heat transfer surface area (m^2)
AR	aspect ratio of rectangular channel (width/height)
Buo	rotational buoyancy parameter (see Eq. (8))
d	hydraulic diameter (mm)
e	rib height (m)
h	heater transfer coefficient ($W/(m^2\,K)$)
I	the current of the heater (A)
Nu	regionally averaged Nusselt number on each segment (see Eq. (5))
$\overline{Nu}$	surface averaged Nusselt number on the whole leading or trailing side
P	rib pitch (m)
Q	heat energy (W)
r	radius (m)
Re	Reynolds number (see Eq. (6))
Ro	rotation number (see Eq. (7))
T	temperature (K)
U	mean average velocity of coolant (m/s)
V	the voltage of the heater (V)

Greek symbols

α	heat loss coefficient (W/K)
β	angle of channel orientation
μ	viscosity of the coolant (Pa s)
λ	thermal conductivity of the coolant ($W/(m^2\,K)$)
Ω	rotate speed (rpm)
ρ	density of the coolant (kg/m^3)

Subscripts

b	bulk
e	environment
h	hydraulic
i	local parameter
in	inlet of the heated channel for heated section
loss	loss
net	net
out	outlet of the heated channel for heated section
s	stationary
w	wall
0	fully-developed turbulent flow in non-rotating smooth round pipe
1	inlet pass
2	outlet pass

the local heat/mass transfer distributions. However, stationary models neglect the effects of the Coriolis and buoyancy forces that occur under rotating conditions which alter the velocity, turbulence and temperature distribution. So experiments with rotation have been conducted to model engine cooling environments more closely. Wagner et al. [5,6] systematically conducted experimental investigations on heat transfer in a four-pass rotating smooth channel. They found that the Coriolis force had a positive effect on heat transfer of trailing wall but negative effect on leading wall in the first radial outward passage. Moreover, critical Rotation number on leading wall of radial outward flow channel was observed. Dutta et al. [7] reviewed the experimental data of Wagner et al. and conducted a computational study over rotating smooth U-duct. They proposed a mechanism-base explanation that there was reverse flow induced by the interaction of Coriolis and buoyancy forces near the leading wall. In 2013, Deng et al. [8] conducted extensive experimental investigations on heat transfer in a rotating smooth U-duct at high rotation numbers (Ro: 0–2.08). They found that the relationship between critical rotation number (Ro_c) and dimensionless location (X/D) on the leading wall of first passage obeys a simple rule $Ro_c{\cdot}X/D = 1.31$.

Cross-section shape is another critical factor in the mechanism of the second flow formation and strength, which will affect the heat transfer in the rotating channel. Many researchers focused on square and rectangular cross-section channels [9–11], and studies were performed to study the heat transfer in different aspect ratio channels with smooth and ribbed walls. Soong et al. [10] conducted tests on the rotating rectangular ducts with aspect ratios of AR = 0.2, 0.5, 1, 2, 5. They found that the heat transfer performances are different for the cross-section ducts with different aspect ratios. And the channel with AR = 1 shows the best heat transfer enhancement for all experimental cases. Taslim et al. [12,13] investigated the heat transfer distribution in square and rectangular ribbed channels under rotation. They found that the effects of rotation were more apparent in ribbed channels with a larger channel aspect ratio. Li et al. [14] investigated the heat transfer distribution in a smooth channel with engine-similar cross-section. They found that the cross-section affected the heat transfer in both stationary and rotating conditions, and the strengths of effect were different.

The channel orientation (β) has shown to alter the development of rotational induced vortices, thus influence the heat transfer in a rotating channel. Parsons et al. [15,16] studied the effects of channel orientation on the local heat transfer coefficients in a rotating two-pass square channel with ribbed walls. They found that the effect of the Coriolis force and cross-stream flow were reduced as the channel orientation changed from the normal $\beta = 90°$ to an angled orientation of $\beta = 135°$. Park and Lau [17] used the naphthalene sublimation technology to investigate the effect of channel orientation on the heat transfer in a smooth rotating channel. The results showed that the orientation of the rotating two-pass channel significantly affected the local mass transfer distribution on the first pass of the channel, due to the rotational Coriolis in the diagonally oriented channel induced secondary flow and shifted the high stream wise velocity diagonally. The same results were obtained in the investigation of Dutta and Han [18]. Then, Huh et al. [19] performed a study on a rectangular channel with smooth and ribbed wall. They draw the conclusion that in the smooth case, the channel orientation was important and beneficial to the enhancement of heat transfer on the leading surface in the first pass.

Furthermore, due to the geometric characteristics of serpentine internal cooling channels, the effect of the entrance condition and 180° turn on heat transfer were studied by researches. Wright et al. [20] performed experiments in channels with three different entrance geometries. They concluded that the entrance condition enhanced the heat transfer. They also pointed out that increasing the rotation number would decrease the effect of the entrance. And the ribs also decreased the entrance effect. Cho et al. [21] used a mass transfer method to study the effect of rotation in a rotating two-pass rectangular channel with 70° angled ribs. Their results showed that the rotation effect diminished in the second pass due the 180° turn effect.

In recent years, many experimental and numerical works were performed at $Ro > 1$. Chang and Liou [22–24] investigated the heat transfer distribution in square and rectangular (AR = 1, 2, 4) ribbed channels with rotation number (Ro) in the ranges of 0–1.8 and 0–2,