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Pressure drop and heat transfer performance in a rotating two-pass channel with staggered 45-deg ribs

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ABSTRACT

A rotating two-pass ribbed square channel is applied to perform the pressure drop and heat transfer study. The inlet Reynolds number and rotation number vary from 20,000 to 60,000, and 0 to 1.02, respectively. The regional heat transfer coefficients are obtained by heated cooper plate technique. The rotational pressure drops are measured by the rotation-to-stationary pressure measurement system. The ribs with attack angle of 45-deg are staggered roughened on leading and trailing walls. Due to only one wall-temperature ratio was performed in current study, the isolated buoyancy effect was not able to be disclosed.

The results show that the 45-deg ribs bring 40–80% higher heat transfer for ribbed walls and 15–65% for smooth walls. The rib-to-smooth *Nu* ratio declines with Reynolds number and is more sensible in the second passage. Meanwhile, 150–210% higher pressure drop in ribbed channel is observed compared to smooth one, but this penalty decreases with Reynolds number. Rotation presents more dominant influences on pressure drop in heated channel than unheated one. But rotation-to-stationary friction factors decrease with rotation number for both heated and unheated channel as $Ro < 0.55$, after which an increase trend is observed. The presence of buoyancy effect in heated channel helps to promotes rotational pressure drop variation. Also, ribbed-to-smooth thermal performance is significantly elevated by rotation when rotation number reaches over 0.25. The surface averaged heat transfer coefficients are developed with respect to buoyancy parameters.

1. Introduction

The improvement of the efficiency and power production of gas turbine engines requires higher turbine inlet temperature which has exceeded the melting points of the turbine blade material. In order to guarantee their safe operation, turbine blades need to be cooled by sophisticated cooling techniques. Researches on turbine blade internal cooling have been initiated and conducted by different organizations to improve the design of gas turbine [1–3]. Among all the factors related to the rotating internal cooling channel, the rotational heat transfer performance and pressure drop are of significant for turbine blade designers. Over the past several decades, the rotational effects in a rotating channel have been studied by many previous works.

1.1. Rotational effects on heat transfer with smooth walls

In rotating conditions, the coolant inside the channel experiences Coriolis and rotation induced buoyancy forces. The flow field is strongly affected by rotation and thereby the heat transfer. Heat transfer difference between trailing and leading surfaces due to rotation was found in a four-pass smooth channel [4,5]. Rotation presented positive effect on heat transfer of trailing wall but negative effect on leading wall in the first radial outward passage. And the reverse was true for the second radial inward passage due to the flow direction changed. A numerical study was conducted to explain the interaction of Coriolis and buoyancy forces near the leading wall [6]. Furthermore, correlations were developed to summarize the rotation effects on heat transfer in a four-pass square serpentine smooth channel [7,8]. The rotating-to- stationary *Nu* ratio was found to be a function of the product of rotation number and X/D_h. The couple effects between Reynolds number and rotation number were also studied in a rotating 4:1 aspect ratio smooth coolant passage [9]. Rotational heat transfer

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Nomenclature

English symbols

A	area (m^2) or the correlated coefficients in non-rotating cases
Buo	buoyancy parameter
D_h	hydraulic diameter (m)
f	Fanning friction factor
h	heat transfer coefficient ($W/(m^2 \cdot K)$)
I	the current of each heater (A)
K	pressure drop factor
L	the flow length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
n	exponents for Reynolds number in non-rotating cases
P	pressure (Pa)
Pr	Prandtl number
Q	heat energy (W)
R	resistance of heater (Ω)
r	rotating radius (m)
Re	inlet Reynolds number
Ro	inlet rotation number
T	temperature (K)
U	mean velocity (m/s)

Greek symbols

α	heat loss coefficient (W/K)
Ω	rotation rate (rad/s)
η	thermal performance
μ	viscosity of the coolant (Pa·s)
ρ	density (kg/m^3)
λ	heat conductivity coefficient (W/(m·K))

Subscripts

ave	averaged
b	bulk
cu	copper plate
i	the number of the measured point in X direction
in	inlet for heated channel
loss	loss
net	net
out	outlet
s	stationary
smooth	result obtained in the channel without ribs
w	wall
0	fully-developed turbulent flow in non-rotating smooth circular pipe

of the leading wall increased with rotation number only at low Reynolds number, and declined at high Reynolds number for radially outward flow passage.

The buoyancy parameter effect was studied for heated condition consideration [10,11]. The rotational *Nu* ratios increased with buoyancy parameter on the pressure side and decreased on the suction side for the radial outward passage. And the influence magnitude of buoyancy parameter was in the same approximate qualitative manner as the rotation number changed. A series of extensive experimental investigations were conducted to determine the critical rotation number variation [12–14]. It was found that the critical rotation number of first passage leading wall had a deep relation with the dimensionless location, channel orientation and wall temperature ratio.

1.2. Rotational effects on heat transfer with rib-roughened walls

In real turbine blade application, the internal coolant wall is roughened with ribs. When the ribs were added, rotation and buoyancy presented less effects on the wall heat transfer than the smooth case [15,16]. And the characteristic of the flow and heat transfer in ribbed channel became extremely difficult to predict. The Nusselt number ratio of partially unstabilized ribbed sides showed a mixed dependence on the rotation number in a two-pass rib-roughened triangular channel [17]. At higher rotation numbers, similar heat transfer trends with rotation number were observed [18,19]. Also, the uneven wall temperature was found to have a significant impact on the local heat transfer coefficients in a rotating duct with angled rib turbulators [20].

The effect of rib arrangement was studied in a two-pass channel [21]. Rotation caused higher heat transfer with 45-deg parallel ribs than the 45-deg crossed ribs for the first pass trailing and second pass leading walls. The rib spacing effect was also investigated to determine the optimal pitch-to-height ratio [22–24]. The very close rib spacing of $p/e = 3$ had the best thermal performance and the $p/e = 5$ spacing brought with the greatest pressure penalty in both rotating and non-rotating channels.

1.3. Rotational effects on friction and thermal performance

Inserting ribs in rotating channels can enhance the heat transfer than the smooth case, but it also brings with severe pressure drop penalty. The rotation-to-smooth friction factor in a two-pass smooth channel was found to increase with rotation number [25]. Adding ribs caused around 4 times pressure loss than smooth channel at stationary, but this penalty decreased with rotation number [26]. The highest pressure drop appeared in the turning region at stationary, but in the upstream region of the second pass at rotating cases [27].

By considering the combined effect of Coriolis force, rotating buoyancy and the geometric features, the friction coefficients in a parallelogram ribbed channel were raised to 1.05–5.2 times of the stationary levels, leading the thermal performance factors to the range of 0.979–1.575 [28]. Ribbed channel had higher thermal performance than smooth channel as rotation number increased over 0.3 [29]. Among different aspect ratios, the 1:4 channel achieved the best thermal performance since it brought with the lowest pressure drop [30].

1.4. Objectives of current study

As stated above, the regional heat transfer distribution, pressure drop in a rotating smooth or ribbed channel have been tested and discussed. However, some new characteristics in averaged heat transfer on ribbed and smooth walls, rotational pressure drop comparisons, and the rib-to-smooth parameters are deserved to study in a 45-deg ribbed channel. The current study extends the work of Deng and Qiu et al. [12,25] by considering the effects of the inserting staggered ribs. The current work aims to provide additional information for overall perspectives in such 45-deg ribbed channel with respect to high rotation numbers and buoyancy parameters.