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PIV flow measurements for a rotating square smooth channel heated by basically uniform heat flux

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ABSTRACT

In this paper, we experimentally investigated the mainstream and secondary flow in a smooth rotating channel with wall heated by particle image velocimetry (PIV). The hybrid effect of Coriolis force and buoyancy force on the mainstream and secondary flow was taken into consideration in the current work. In the experiments, the Reynolds number, based on the channel hydraulic diameter (D = 80 mm) and the bulk mainstream velocity (V_m = 1.82 m/s), is 10,000, and the rotation numbers are 0, 0.13, 0.26, 0.39, respectively. Constant heat flux on the four channel walls are provided by Indium Tin Oxide (ITO) heater glass, the density ratio (d.r.) equaling approximately 0.1. The buoyancy number ranges from 0 to 0.153. The results showed that Coriolis force and buoyancy force have important influences on the flow field in rotating channels. Coriolis force pushes the mainstream to trailing side, making an asymmetry of the mainstream. On the cross-section, there is a symmetric two-vortex pair caused by the Coriolis. The two-vortex pair is pushed into the trailing side with the increase of rotation numbers. Then, there are two small vortex appearing near the leading side. Buoyancy force suppresses mainstream and causes the separation of the flow near the leading side. When the separated flow happened, the structure of secondary flow is disordered near the leading side.

1. Introduction

Internal cooling technology is one of the most difficult task in gas turbine blades. Over the past several decades, a vast amount of studies dealing with internal cooling of turbine blades have been reviewed by Han and Huh [1]. However, limited by the complex measurement technology under rotating conditions, most of the experimental investigations focused on the heat transfer instead of the velocity measurement. In rotating channels, Coriolis force and buoyancy force are two important forces that affect the flow behavior and heat transfer significantly.

In rotating channels, Coriolis force pushes mainstream to trailing side and induces secondary flow. The direction of buoyancy force is opposite to the direction of fluid in a rotating channel. The mechanism of the flow field in a rotating channel is important for engine designers. Many investigators have studied the flow field in rotating channels experimentally. However, many investigators studied the mainstream field without wall heated, which mainstreams only Coriolis force was considered. In recent years, buoyancy force begins to be taken into consideration on flow field in rotating channels because that buoyancy force has changed the flow and heat transfer distribution in rotating channels. We divided the published work focusing on mainstream and secondary flow in rotating channels into three parts:

1.1. Effect of Coriolis force on mainstream

Coriolis force is generated by rotation, the effect of which can be measured by the rotation number:

$$Ro = \frac{\Omega D}{V_m} \tag{1}$$

where Ω is the rotating speed, D is the hydraulic diameter, and V_m is the average bulk flow velocity.

The effect of Coriolis force was numerically investigated in Refs. [2,3], and experimentally investigated in Refs. [4–10]. Both of investigators found that the mainstream velocity profile is pushed to trailing side by Coriolis force, and the turbulent Reynolds stresses are asymmetric. They also found that rotation stabilizes the flow on leading side and destabilizes the flow on trailing side. They reported that, on the stabilized layer, the turbulent stress

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Nomenclature

Buo	rotational buoyancy number (see Eq. (2))
d.r.	density ratio
D	hydraulic diameter (m)
I	turbulent intensity
M	magnification factor (pixel/mm)
Nu	Nusselt number
r	radius (m)
Ro	rotation number (see Eq. (1))
T	temperature (K)
V	velocity (m/s)
X	X-axis direction
Y	Y-axis direction
Z	Z-axis direction

Greek symbols

Ω	rotating speed (rpm)
ν	kinematic viscosity
ρ	density of the coolant (kg/m^3)

Subscripts

b	bulk flow
c	critical point
m	average mainstream
x	component of X-axis direction
y	component of Y-axis direction
f	fluid
w	wall/watt
0	fully-developed turbulent flow in non-rotating smooth round pipe

decreases, which is also found by Hart [11]. Cheah et al. [12] measured the main flow at symmetry plane of the U-ducts by LDV (Laser Doppler Velocimetry) under rotating condition, and they obtained the same impact of the Coriolis force on the mainstream with Andersson, Johnson and Hart. The effect of rotation was also carried out by measuring pressure drop in a rotating duct [13], and the results show that the friction coefficient increases with rotation numbers. Liou et al. [14] used LDV to conduct the spectral analysis of flow field in a rotating duct. They found that Coriolis force promotes mixture of core and near-wall fluids. Visscher and Andersson [15] using PIV measured the separated turbulent flows with rotation. The length of the primary separation bubble decreases monotonically with the increase of rotation on leading side. Gallo and Astarita [16], Sante and Braembussche [17] all investigated the mainstream field in rotating channels. Gallo performed a reconstruction and vertical field of the mainstream to study the influence of rotation by PIV. Sante also presented a quasi-3D view of flow to illustrate the impact of Coriolis force in a rotating channel, using TR-PIV (time resolved particle image velocimetry). They found that the boundary layer thickness increases on the leading side and decreases on the trailing side. The turbulence intensity moves away from the leading side and remains close to the trailing side. They also found the hairpin vortices on the trailing side at the mid-channel planes.

1.2. Effect of Coriolis force on secondary flow

When the channel is rotating, secondary flow will be generated in the cross-section, which is an important factor affecting the flow and heat transfer in the channel.

Nandakumar et al. [18], Iacovides and Launder [19] investigated the secondary flow numerically in rotating channels, respectively. Nandakumar et al. found four vortices in the cross section, and the structure of vortices changes with the rotation numbers. While Iacovides and Launder found two small vortices in the cross section on the trailing side. Iacovides and Launder also found that Nusselt number increases on trailing side. Secondary flow was investigated using PIV by Gallo [20] and Elfert [21]. In Ref. [21], investigators compared the flow field data with heat transfer data, and identified several connections between Nu/Nu_0 and two fluid dynamics quantities turbulent kinetic energy (TKE) and normal-to wall velocity component (w). They found that with the increase of TKE, the heat transfer increases. Elfert presented secondary flow at different positions to explain the effect of rotation. Macfarlane and Joubert [22] studied the effect of secondary flow on developing turbulent boundary layers under rotating conditions. They presented the experimental results about the interaction between secondary flows and developing rotating turbulent boundary layers, and found that the boundary layer is initially subject only to the effects of the Coriolis, then the specific effects of the secondary flows are observed. And the shear stress intensities are the most sensitive to secondary flows.

1.3. Effect of buoyancy force on mainstream and secondary flow

Buoyancy force is another important force in a rotating channel, which is induced by the temperature gradient near the wall. Buoyancy force has an important influence on the characteristics of flow and heat transfer. For a radial outward channel, buoyancy force is in the opposite direction to the direction of mainstream, suppressing the flow field near the leading side. The dimensional parameter characterizing the effect of rotation is buoyancy number:

$$Buo = Ro^2 \frac{r}{D} \frac{T_w - T_f}{T_w} \tag{2}$$

where r is the rotating radius, T_W is the wall temperature, and T_f is the temperature of fluid. With the increase of rotating radius, the effect of rotation buoyancy force is enhanced. Siegel [23] studied the buoyancy effect on heat transfer in a rotating tube by CFD, and found that buoyancy tends to improve heat transfer at the radial inward pass and reduce heat transfer at the radial outward pass. The buoyancy force is generated by the heated wall, which mainstreams that the condition of the heated walls will affect the buoyancy force. The results is confirmed by Han and Zhang's [24] experiments. They [24] investigated the effect of uneven wall temperature on local heat transfer with various thermal boundary conditions: (A) four walls with uniform temperature, (B) four walls with uniform heat flux and (C) leading and trailing walls hot and two side cold. The investigation showed that the value of Nu/Nu_0 on the leading side for three cases is case B > case C > case A, and on the trailing side is case A > case C > case B. However, on the trailing side the differences of Nu/Nu_0 among the three cases decreases compared with those on leading side. The results they obtained suggest that the local uneven wall temperature creates the local buoyancy forces, which changes the effect of the rotation. Therefore, the local heat transfer coefficients are altered on the leading, trailing and side surfaces. Han and Dutta [25] continued their investigation by predicting the flow field in a rotating channel with Coriolis force