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Experimental investigation on the effect of turbulent intensity on heat transfer in a square rotating channel

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ABSTRACT

In this paper, we experimentally investigated the effect of turbulent intensity on heat transfer in a square rotating channel. The grid generated turbulence is measured by hot-wire, and the heat transfer coefficient is measured by TLCs. In the experiment, the Reynolds number, based on the channel hydraulic diameter ($D = 80$ mm) and the bulk mean velocity ($V_m = 1.82$ m/s), is 10,000, and the rotation number ranges from 0 to 0.52. The mean density ratio (d.r. $= (T_w - T_b)/T_w$) is about 0.1 in the current work using transparent heater glass (Indium Tin Oxide) to provide uniform heat flux. Two different turbulent intensity of inlet air (0.6% and 5.5%) are taken into consideration to investigate the heat transfer distribution on the leading and trailing side. The results show that turbulent intensity has an effect on heat transfer on both leading and trailing side, especially at rotating conditions. At static conditions, the effect of turbulent intensity on heat transfer is not obvious. However, with the increase of rotation number, in case B with a medium turbulent intensity (Tu) of 5.5%, the Nu/Nu_0 is about 10% higher than that in the case A with low turbulent intensity of 0.6% with the rotation number of 0.52 at X/D = 2 on trailing side. The enhancement of case B decreases along X/D directions. On the leading side, the turbulent intensity has same effect on heat transfer with that on trailing side, but not as prominent as that on the trailing side. In current work, the turbulent intensities at different X/D directions are also presented to explain the phenomenon of heat transfer in the channel. More detail of results will be presented in this paper.

1. Introduction

The increasing demand on the high efficiency of gas turbine engines requires the engine designers to develop effective cooling technologies because the gas temperature at the inlet of turbine is far beyond the working temperature even melting point of material. To resolve this conflict, lots of cooling techniques are applied to protect the turbine blade. Internal forced convection is one of the most classical and popular methods used to keep an appropriate temperature in the blade material. As one of the effective types for the internal forced convection, serpentine passage in the middle section of a turbine blade has been investigated, improved, and applied in the turbine blades more than thirty years. Over the past several decades, a vast amount of studies dealing with internal cooling of turbine blades have been reviewed by Han [1,2].

Among all the investigations on heat transfer in rotating channels, we can divide these papers into two parts: focusing on flow parameters and focusing on the geometry parameters.

Investigations on flow parameters:

In 1989, Wagner and Johnson [3,4] found that four parameters determine the heat transfer in a rotating passage: coolant-to-wall temperature ratio, Rossby number (rotation number), Reynolds number and radius-to-passage hydraulic ratio. Then many researchers started to investigate the heat transfer in a rotating channel based on these four parameters. Kukreja et al. [5] used the Naphthalene sublimation technology to investigate a rotating two-pass square channel. They found that the rotation-induced Coriolis increases the mass transfer on the trailing wall reduces the mass transfer on the leading wall. Kuo and Hwang [6,7] found that in an outward flow channel, rotation weakens heat transfer on leading side, with the increase of rotation numbers, heat transfer is enhanced on the leading side. The same results were also obtained by Iacovides et al. [8]. Deng [9] investigated the effect of rotation numbers on the heat transfer in a rotating smooth square channel. The results showed that the heat transfer in the channel decreases at a relatively lower rotation number ($Ro < 0.35$) for both inlet and outlet passes. While at high rotation number ($Ro > 0.35$), heat transfer decrease on both leading and trailing walls in the first pass, and increase in the second pass.

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Nomenclature

A	heat transfer surface area (m^2)
Buo	rotational buoyancy parameter (see Eq. (10))
C_p	specific heat capacity
d. r.	density ratio
D	hydraulic diameter (mm)
h	heater transfer coefficient ($W/(m^2 K)$)
HSV	Hue, Saturation, Value
ITO	Indium Tin Oxide
TLCs	Thermography Liquid Crystal
Nu	Nusselt number (see Eq. (7))
Pr	Prandtl number
q	heat flux rate (W/m^2)
r	rotation radius (m)
RGB	pixel Red, Green and Blue values
Re	Reynolds number (see Eq. (8))
Ro	rotation number (see Eq. (9))
T	temperature (K)
Tu	Turbulent intensity
u	instantaneous velocity of coolant (m/s)
V	velocity of mean flow
X	stream-wise direction
Y	normal to wall direction

Greek symbols

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)
δ	thickness of Plexiglas

Subscripts

b	bulk
e	environment
f	fluid
in	inlet of the heated channel for heated section
joule	joule power
loss	loss
m	averaged value
net	net
plexi	Plexiglas
w	wall
0	fully-developed turbulent flow in non-rotating smooth round pipe

Investigations on geometry parameters:

As for the geometry parameters, it always contains rotation orientation (β), channel aspect ratio (AR), different shapes of ribs, and so on. Liou, Chang and Chen investigated the effect of different kinds of ribs on heat transfer in rotating channels [10–12]. They found that detached ribs create more uniform heat transfer distributions on the leading and trailing walls than attached ribs. Kuo et al. [13] and Soong et al. [14] conducted a series of tests on the rotating rectangular ducts with aspect ratio of AR = 0.5, 1, 2 and AR = 0.2, 0.5, 1, 2, 5, respectively. They found that the heat transfer distribution si different with different aspect ratios. They found that the channel with AR = 1 shows the best heat transfer enhancement among all the experimental cases. They also concluded that the Coriolis-induced second flow provides a positive effect on the heat transfer enhancement, while the buoyancy forces have the negative effect. Murata and Mochizuki [15] investigated the effect AR on heat transfer in rotation channels numerically. The AR ranges from 0.25 to 4. They draw the conclusion that secondary flow is induced by Coriolis force and the fluctuating components of Coriolis influence the turbulent flow indirectly and directly. In addition, Kuo et al. [13] and Soong et al. [14] also found the same results with Murata. Park [16] used the naphthalene sublimation technology to investigate the effect of channel orientation to the heat transfer in a smooth rotating channel. They found that the channel orientation affects the local mass transfer distribution in the first pass of the channel significantly. The same results were obtained by Dutta [17]. Later, Huh [18] performed a study on a rectangular channel with smooth and ribbed wall. They draw the conclusion that in the smooth case, the channel orientation is important and beneficial to the enhancement of heat transfer on the leading surface in the first pass.

As mentioned above, heat transfer investigations in rotating channels have been performed for decades of years. However, most of investigations focus on flow parameters and geometry parameters. To author's best knowledge, only less of the paper focusing on the quality of coolant air in rotation channel, which is the main factor that affect the heat transfer in rotating channels. Therefore, we focus on the effect of different inlet condition of coolant air on heat transfer in rotation channels. In the current work, two different inlet conditions: (Case A: inlet coolant air with a low turbulent intensity of 0.6%; Case B: inlet coolant air with a medium turbulent intensity of 5.5%) are taken into considerations. Heat transfer distributions are measured by TLCs, the Reynolds number is 10,000, and the rotation number ranges from 0 to 0.52. To explain the heat transfer phenomena, turbulent intensity at static conditions are measured by hot-wires.

2. Experiment setup and measure procedure

2.1. Rotating facilities

The experiments present herein were performed on the advanced flow and heat transfer rotating facility in National Key Laboratory of Science and Technology on Aero Engines Aero-thermodynamics, which has been mentioned in paper [19]. The rotating facility consists of a rotating disk, where all the test section and data acquisition modules are mounted. Extension of the rotating arms are used to make the total length of the rotating radius can be up to 0.98 m. The rotating frame is driven by a DC motor. The coolant air, provided by a blower, passes through the flow meter, rotary joint, settle chamber (Screen & Honeycomb), and then enters into the test section. A balance weight is on the opposite side of the disk to ensure the balance of the rotating system. Thermocouples are used for measuring the temperature on the rotating frame. All the cold ends of thermocouples are placed on the aluminum-made rotating disk. Due to the good performance of thermal conductivity of aluminum, the temperature of the disk is relatively constant and even. The absolute temperature of the rotating disk is measured by a thermal resistance. The analog signals of the thermocouple are converted into digital ones before transmitted to the non-rotating facilities by signal slip rings. The heating slip ring is used for conveying the current (up to 2 A) for heating the channel (see Fig. 1).

2.2. Test section

The sketch of the test channel is shown in Fig. 2 and the experimental variables are shown in Table 1. The test channel has a