Experimental Thermal and Fluid Science 88 (2017) 530–541

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Heat transfer in a rotating trailing edge wedge-shaped cooling channel with two inflow forms

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ARTICLE INFO

Article history:
Received 25 April 2017
Received in revised form 22 June 2017
Accepted 14 July 2017
Available online 15 July 2017

Keywords:
Blade trailing edge
Wedge-shaped channel
Rotating heat transfer
Inflow forms

ABSTRACT

Heat transfer performances are experimentally investigated in a rotating trailing edge wedge-shaped cooling channel. Two coolant inflow forms (bottom inlet and top-lateral inlet) and two channel orientations ($\beta = 90°$ and $\beta = 135°$) are discussed. The inlet Reynolds number and rotation number vary from 10,000 to 20,000 and 0 to 1.1, respectively. Regionally averaged wall heat transfer coefficients are measured in stream-wise and span-wise directions.

Rotation substantially elevates heat transfer of the inner wide region which has the lowest heat transfer in non-rotating cases due to side-wall ejection. High-radius region presents higher rotational heat transfer enhancement than low-radius region. Although Coriolis force works direct to pressure side, rotation also brings enhanced effect on suction side heat transfer at $\beta = 90°$ case. Trailing-to-leading wall heat transfer differences are significantly reduced by top-lateral coolant inlet impingement and channel orientation of 135°, and decreases along the stream-wise direction at $\beta = 90°$ channel. A wide range of correlations between Nu/Nu_s ratios and buoyancy parameters are developed.

1. Introduction

Modern advanced high-performance gas turbines operate at high turbine inlet temperature, witch far exceeds the melting point of turbine blade material. The thermal stress caused by high turbine inlet temperature would influence the normal work of turbine blades. Thus, various efficient cooling systems are developed to protect blades from damage. Internal cooling is one type of classic and popular method used to protect the turbine blades [1–3]. Turbine blade trailing edge is the most challenging area in turbine cooling, due to the limited space for taking effective cooling methods. The constrains from turbine blade bring a series of distinctive characteristics in this region, such as wedge-shaped converging cross-section with high aspect ratio, lateral fluid extraction, pin–fin arrays roughened wall and large angled channel orientation [4,5].

In the channel with lateral fluid extraction, the local mass flow rate changes in both stream-wise and span-wise, which means it is difficult to determine the local Reynolds number and the bulk temperature. It was found that the overall heat transfer was reduced by introducing the side-wall ejection [6,7]. The heat transfer coefficients enhanced on the narrow side of wedge-shaped channel at the cost of decline on the wide side [8]. Similar observation was also reported that the narrow side showed the most significant heat transfer enhancement [9]. A large flow separation vertex occur near the end of the wide side of wedge-shaped with lateral fluid ejection channel which caused low local heat transfer level without rotation [10]. In a rotating smooth wedge-shaped channel with lateral fluid discharge, heat transfer on both leading and trailing walls were enhanced by rotation [11]. Rotation elevated heat transfer on the inner region mainly [12,13]. Also, less mass flow split at the slots near the channel inlet when the channel was rotating [14], and weaken the large separation vortex induced by lateral ejection. But the stream-wise heat transfer were still declined, thus introducing a second coolant in the top-inner region significantly affected the local heat transfer [15,16]. Adding tapered ribs and pin-fins reduced the rotational effect, especially narrow region near the slots [17,18]. Same conclusion was obtained in a rotating rib-roughed wedge-shaped channel with or without lateral flow holes [19]. In a 30:1 scaled wedge-shaped model, rotation caused 5–10% heat transfer enhancement in radial outward region, but brought 10% decline at lateral outflow region [20,21].

Generally, cooling channels located in the tailing edge of turbine blade have a high aspect ratio (AR > 1). The aspect ratio is a

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http://dx.doi.org/10.1016/j.expthermflusci.2017.07.008
0894-1777/

Nomenclature

English symbols

A	area (m^2)
Buo	buoyancy parameter
D_h	hydraulic diameter (m)
h	heat transfer coefficient ($W/(m^2 \cdot K)$)
I	the current of each heater (A)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
n	rotational speed (r/min)
Pr	Prandtl number
Q	heat energy (W)
R	resistance of heater (Ω)
r	rotational radius (m)
Re	inlet Reynolds number
Ro	inlet rotation number
T	temperature (K)
U	mean velocity (m/s)
X	coordinate direction (m)

Greek symbols

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

Subscripts

ave	average
b	bulk
cu	copper plate
e	environmental parameter
i	the number of the measured point in X direction
in	inlet for bulk temperature calculation unit
$inlet$	inlet for heated channel
$loss$	loss
net	net
out	outlet for slots
s	stationary
w	wall
0	fully-developed turbulent flow in non-rotating smooth circular pipe

key parameter in heat transfer mechanism research, it provides a favorable condition for influencing the magnitude of Coriolis force, and therefore changed the heat transfer distribution through inducing the secondary flow [22]. An experimental study in a rotating rectangular channel with staggered pin–fin array (AR = 10:1) showed the impact on both trailing and leading side heat transfer of Coriolis force and the buoyancy force [23]. The interaction between the primary and secondary flow fields in a rotating smooth channel was experimentally studied with PIV method, the effect of normal pressure gradient term and Coriolis term was also analyzed [24]. The AR = 4:1 channel was typically considered to focus on the aspect ratio effect. Significant span-wise variation in the heat transfer distribution due to rotation was observed [25]. It was also observed that heat transfer on both leading and trailing sides could be enhanced by rotation [26]. The trailing-to-leading heat transfer difference was reduced by increasing the aspect ratio [27]. The critical number phenomenon was observed in the rectangular channel with AR = 4:1 [28]. When rotation number beyond this value, the heat transfer ratio would present a reverse tendency.

It was found that the channel orientation play an important role in influencing heat transfer of a rotating channel with lateral fluid extraction. The Coriolis force pointing to different position for different channel orientation, in consequence the patterns of main flow and secondary flow were diverse, in turn affecting the heat transfer distribution of both leading and trailing walls [5,12]. A numerical simulation studied several channel orientation in rotating smooth wedge-shaped cooling channel, founding out that the different heat transfer distribution due to changing channel orientation produced significant differences in the flow field [14]. The trailing-to-leading heat transfer difference was reduced by varying the channel orientation from 90° to 135° [29].

As mentioned above, very low heat transfer was observed at the top-inner region in a radial outward wedge-shaped channel due to lateral fluid extraction. This issue should be concentrated and a two-inlet cooling concept was introduced [15]. Heat transfer performances of three different second inlet locations were investigated through experimental approach [30]. The heat transfer performances in a two-inlet rectangular channel and wedge-shaped channel were presented with rectangular second inlet [16,31]. It was found that the top rectangular coolant inlet shows remarkable enhancement on high-regions heat transfer. Also an optimized rotating two-inlet wedge-shaped channel with four circular inflow holes was bring out, heat transfer performance was studied in both rotating and non-rotating situation [32].

However, before the two-inlet cooling investigation, the comparisons between two single-inlet cases deserve to be discussed in detail. So, the current study extends studies [12,15,31] by considering the heat transfer characteristic in wedge-shaped smooth channel with two different inflow forms separately. Coolants flow from bottom inlet and top-lateral inlet are introduced. Also, two channel orientation conditions, which represent the basic one and realistic one, are compared in detail. Thus, the current work aims to not only enlarge the range of rotation parameters upon previous single bottom inlet rotating wedge-shaped cooling channel, but also to introduce a top-lateral coolant flow inlet to observe new heat transfer phenomenon on the basis of bottom inlet. By providing these additional information for heat transfer performance, there will be more basic heat transfer explanations for further research of rotating two-inlet cooling. And through this fundamental research, looking forward to provide the corresponding heat transfer correlations which can be applied in the engineering.

2. Experimental apparatus

2.1. Rotating facility

Fig. 1 shows the rotating facility that consists of four main parts: electric motor, rotating arm with the support, temperature measurement module, slip rings. The coolant mass flow rate is controlled by an electromagnetic valve and is measured by FCI-98 thermal flow-meter. The coolant travels through a two-pass rotary union (inlet port), through the horizontal hollow shaft, turns 90°