Chinese Journal of Aeronautics, (2018), 31(3): 457–469

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Experimental research in rotating wedge-shaped cooling channel with multiple non-equant holes lateral inlet

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Received 28 December 2016; revised 16 March 2017; accepted 5 May 2017
Available online 31 January 2018

KEYWORDS

Heat transfer;
Lateral inlet;
Rotor blades trailing edge;
Rotating;
Wedge-shaped channel

Abstract The heat transfer in a novel smooth wedge-shaped cooling channel with lateral ejection of turbine blade trailing edge is experimentally investigated in both non-rotating and rotating cases. Beside the conventional inlet at the bottom of the channel, an extra coolant injection from 8 lateral non-equant holes is introduced to improve the overall heat transfer. The total mass flow rate ratio (lateral mass flow rate/total mass flow rate) varies from 0 to 1.0. The major inlet Reynolds number and rotation number respectively vary from 10000 to 20000 and from 0 to 1.16. Experimental results show that the lateral inlet decreases local bulk temperature and increases local heat transfer at the middle and the top of the static channel. In rotating cases, the lateral inlet notably improves the heat transfer at the high-radius half channel and compensates the negative effects induced by the rotation. Both intensity and uniformity of heat transfer inside the channel are enhanced while flow resistance decreases with proper mass flow rate ratio of coolant from two inlets. The most satisfactory total mass flow rate ratio is around 2/3. This new structural style of cooling channel has huge potential and provides new direction of heat transfer of turbine blade trailing edge.

1. Introduction

Demands of higher efficiency of modern advanced gas turbines require them operate in a temperature higher than the melting point of the blade, to promote the development of both internal and external cooling techniques to enhance turbine heat transfer. Previous experimental studies on internal cooling technology of advanced gas turbines have been summarized

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.01.013
1000-9361

by Han and Huh[1–3] Internal cooling approaches vary with different parts of the turbine to respond to different needs and achieve the best cooling effect. The trailing edge is one of the most challenging regions due to typically narrow cooling channels. The structural features of the turbine trailing edge can be summarized as follows: wedge-shaped converging cross-section, pin-fin or other turbulence promoters, lateral coolant ejection and large installation angle. Coriolis force and buoyancy force generated in a rotating state make the flow and heat transfer inside the channel further complicated.

Under static condition, many studies have been done and confirmed that the flow and heat transfer of turbine trailing edge are mainly influenced by pin-fin cooling configuration and cooling channel structure. Lateral ejection is one of the most effective characteristics. Lau et al.[4,5] studied a pin-fin cooling channels with lateral ejection structure. The results showed that the decreasing rate of mass flow along the channel caused by the lateral ejection reduced the downstream heat transfer of the channel and further affected the overall heat transfer. Wright and Gohardani[6] found that the heat transfer of both rectangular channel and wedge-shaped channel is uniform in the cross-section without lateral ejection, and the lateral ejection structure is very effective in increasing the heat transfer coefficient near the outflow holes. Kumaran et al.[7] confirmed Lau's conclusion and found that the length of ejection holes had little effect on the channel heat transfer by comparing the heat transfer three different channel configurations pin-fin roughened channel with short lateral ejection holes, with long ones and without lateral ejection holes. McMillin and Lau[8] studied a pin-fin arrayed rectangular channel with naphthalene sublimation technique and drew the conclusion that the turning of main flow caused by side-wall ejection generated higher mass transfer near the ejection but lower near the opposite inner region. Taslim et al.[9] studies a wedge-shaped channel with lateral ejection and observed a significant span-wise heat transfer difference due to the trapezoidal converging configuration. It was also found that this span-wise heat transfer variation can be apparently weakened by the side-wall ejection. Hwang et al.[10] conducted experiments involving eight wedge-shaped channels with different pin-fin and outlet configurations to study the effect of lateral-to-total flow ratio. It was found that the heat transfer was the worst when the ratio approached to 0.3. Hwang and Lu[11] confirmed that the effect of lateral-to-total was a main factor as well as pin shape after further study via transient liquid crystal technique. The worst heat transfer happened when the ratio approached 0.3–0.4 depending on different pin shape. Kan et al.[12] did numerical simulation of flow and heat transfer in a high aspect ratio channel with lateral ejection. It was shown that the heat transfer near the end of channel reduced due to a significant flow separation happened there.

Rotating experimental researches are more challenging than the static ones. Chang et al.[13] found that the heat transfer in a rib roughened wedge-shaped channel with side-wall ejection holes was lower than that without the side-wall ejection ones, especially in a rotating state. However, the experiments were conducted when the installation angle of channel was 90° rather than the real configuration of a trailing edge cooling channel. Wright et al.[14] studied the heat transfer characteristics of a rotating smooth wedge-shaped cooling channel with radial outflow under the channel configuration of 135°. The experimental results showed that the rotation number and buoyancy number are ideal parameters for describing the rotational heat transfer characteristics of the channel. The effect of rotation on the leading surface was greater than that on the trailing surface. There was a critical rotation leading to the obvious change of the heat transfer on the leading surface. Liu et al.[15] did similar investigation but the experiment channel was with lateral ejection. It was found that the lateral ejection weakened the rotation effects and enhanced the overall heat transfer inside the channel for inducing turbulence mixing. The local heat transfer near the outflow slots was especially increased due to a gas film formed near the ejection. Rallabandi et al.[16] added pin-fins inside the channel which enhanced the heat transfer and weakened the effect of rotation. Liu et al.[17] also did experiments with turbulators and obtained similar conclusions. Qiu[18] and Tao[19] et al. experimentally investigated the effects of channel orientation, outlet boundary condition on flow and heat transfer in a rotating wedge-shaped channel with lateral fluid extraction. The results indicated that the channel orientation was an influential factor on channel heat transfer, thus should be chosen carefully to simulate the actual conditions of the turbine. The heat transfer of the channel's inner top region approached the worst point and was sensitive to the rotation effect under the channel configuration of 90°. Srinivasan et al.[20] examined Qiu's experiments[18] by numerical simulation and confirmed that the heat transfer on the trailing wall was enhanced significantly by rotation. Pardeshi et al.[21] numerically investigated more complex situation additionally considering pin-fin/rib turbulators. Li et al.[22] added an additional inlet to wedge-shaped channel at the inner top region and experimental investigated the flow and heat transfer under both rotating and non-rotating conditions. As a result, the second inlet notably improved the heat transfer at the top of the channel and compensated the negative effects induced by the rotation. When the mass flow rate ratio (second inlet mass flow rate/major inlet mass flow rate) came to 0.3, the second inlet benefited overall heat transfer at high rotation numbers.

From the foregoing, previous studies have confirmed that both lateral outlets and inlets have positive effect on heat transfer of the channel and can weaken the impact of rotation. However, adding a second coolant inlet at the top of the channel can only improve the local heat transfer in the vicinity of the inlet but does not benefit the overall heat transfer enough. From the overall perspective, the negative effect of rotation can lead to local overheating of the channel and low efficiency of coolant utilization. The objective of this paper is to further improve the overall heat transfer of turbine trailing edge cooling channel and decrease adverse impact of rotating. Concretely, the second inlet is expanded from one single hole to multiple lateral holes. The radius of those holes varies depending on their location to enhance channel heat transfer uniformity and improve the utilization efficiency of the cooling air by controlling the mass flow rate through different holes. Experiments have been done to research the effect of this new inlet structure under both static and rotating states and the results are summarized.

2. Experiment setup

2.1. Rotating facilities

As shown in Fig. 1, the rotating facility consists of four main modules connected by standard interface, which are electric motor, airing system, rotating arm with support and