Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Xi'an21
18th – 20th October, 2021
www.gpps.global

GPPS-TC-2021-0284

Research status and development trend of rotating internal cooling of a gas turbine blade

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ABSTRACT

Blade internal cooling is crucial for gas turbine thermal efficiency improvement. As an essential component of gas turbine, the investigations on cooling performance of rotor blade is a must. In the paper, the research status of turbine rotor blade internal cooling is illustrated in term of the effect of Coriolis force, buoyancy and cooling channel structure on the cooling performance of rotation internal channel. The three factors have significant influence on the internal cooling performance. Moreover, the development trend of rotating internal cooling is introduced, and novel structure design concept of double wall inner cooling is introduced and simulated as well. The result indicates that the overall heat transfer of the change orientation cooling channel performs better compared to conventional serpentine U-shaped channel due to Coriolis effect. Therefore, that the novel structure cooling channel is promising in the future application.

Key words: blade cooling, gas turbine, rotation

INTRODUCTION

Gas turbine can be classified to aerojet engine, heavy-duty gas turbine, industrial and marine gas turbine and micro gas turbine. It has advantages of high output power, compact size, rapid start and long service life, and thus is widely used in the life and production. To improve the thermal efficiency and output power of gas turbine is crucial to the gas turbine development. Moreover, rotor turbine inlet temperature and compression ratio of compressor are two main parameters to evaluate the thermal efficiency of a gas turbine. Nowadays, F class heavy-duty gas turbine engine operates at temperature around 1400 °C, and G/H/J class heavy-duty gas turbine engine operates at temperature between 1500 °C to 1600 °C (Hongde, et al. 2014). In the future, advanced gas turbine engine is designed to operate at temperature 1700 °C to improve the thermal efficiency and power output of gas turbine (Hongde, et al. 2014). Since the temperature is higher than the permissible maximum metal temperature (1000 °C) of turbine blade, blade external and internal cooling is a must to limit the metal temperature and guarantee blade life (Je-Chin, et al. 2000, Je-Chin, 2000).

Serpentine passages in blade are widely adopted in the blade internal cooling, where coolant air flows through and absorbs thermal energy from the outside of blade. The structure of serpentine passages in rotor blade is depicted in Figure 1. Film cooling is the external cooling used in turbine blade. The principle of the film cooling is that part of coolant utilized for internal cooling is inject to the outside of the blade forming a protective coolant layer between blade outside surface and hot gas path.

To help more engineers and scholars better learn and do research on turbine cooling technology, many literatures have been published to review the cooling technology. Owen, (1988) did a review on research state of air-cooled gas-turbine discs before 1988. H, Iacovides, et al. (1995) presented a review on the gas turbine blade cooling theoretically analysed by using computational fluid dynamics. Je-Chin, et al. (2001) reviewed development of turbine blade internal cooling before 2001. Je-Chin, (2003) reviewed fundamental gas turbine film cooling technology. Besides, Je-Chin, (2004) and Je-Chin, (2014) review recent studies in turbine blade external and internal cooling before 2004. Town, et al. (2007) developed a review on the state-of-the-art cooling design for turbine blades. Wright, et al. (2013) reviewed heat transfer enhancement approaches for turbine blade internal cooling and considered the rotation effect on cooling performance. Bunker, (2017) wrote a paper about the evolution of turbine cooling and the development, current study state and future prospects of turbine cooling were introduced.

Since under rotation condition, many factors such as Coriolis force, buoyance force, cooling channel structure have influence on the internal cooling performance. Hence, the research status and development trend of turbine rotor internal cooling is essential. In the paper, the research status of turbine rotor blade internal cooling is illustrated in term of the effect of Coriolis force, buoyancy and cooling channel structure on the cooling performance of rotation internal channel. Moreover, the development trend of rotating internal cooling is introduced, and the comparison of heat transfer simulation on novel structure design concept of double wall rotation cooling channels has been carried out.

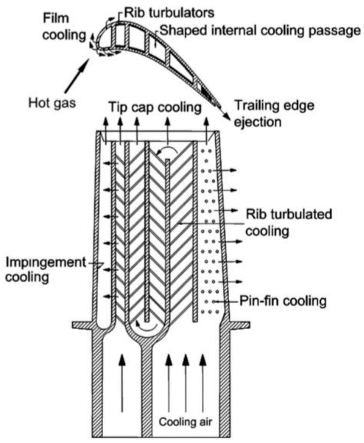

Figure 1 structure of serpentine passages in rotor blade (Je-Chin, 2004)

EFFECT OF CORIOLIS FORCE

Studies on the turbine blade internal cooling have been carried out for several decades. During the late 1980s to the early 1990s, rotation effect on the heat transfer of cooling channel was gradually recognized (Je-Chin, 2014). In this section, the research state in terms of the Coriolis force effect on the rotation internal channel is illustrated.

Compared with stationary cooling channel, the flow field and heat transfer of cooling channel under rotation state are more complex due to the influence of Coriolis force induced by rotation. In the 1970's, some studies (John, 1971, Johnston, et al. 1973, Moore, 1967, Rothe, et al. 1979 and Wagner, et al. 1972) were conducted in rotating circular or rectangular channels without heating to investigate the effect of Coriolis force. The results revealed that there was strong secondary flow induced by Coriolis force in the channels. Figure 2 shows secondary flow and axial velocity distribution in a U-shaped rectangular smooth passage without heating under rotating condition (Je-Chin, et al. 1993). According to Figure 2, in the radial outward flow channel, Coriolis force points to trailing surface from leading surface, leading secondary flow. Because of the secondary flow, axial velocity and heat transfer near the trailing surface is higher than that around leading surface. In the radial inward flow channel, the direction of secondary flow is opposite due to the Coriolis force here pointing to leading surface from trailing surface. Hence, axial velocity and heat transfer near the leading surface is higher than that around trailing surface in the radial inward flow passage.

Kukreja et al. (1998) adopted Naphthalene sublimation technique to analyse the mass transfer distribution on the leading and trailing walls of a U-shaped square smooth passage. The results showed that Coriolis forces improved mass transfer near the trailing side of the radial outward channel, but declined the mass transfer near the leading wall of radial inward pass. While, in the radial inward channel, a reverse trend was obtained. Al-Qahtani, et al. (2002) employed RANS method to theoretically analyse the flow and heat transfer in a U-shaped smooth rectangular passage. The conclusion showed that Coriolis force induced by rotation resulted in secondary flow. The Coriolis force pushed coolant flowing from leading wall to trailing wall in radial outward channel and from trailing to leading in radial inward channel. The similar results that rotation enhanced heat transfer around trailing wall of radial outward flow and leading wall of radial inward flow were concluded by Wagner J H, et al. (1991), Hwang, et al. (1997) and Yang, et al. (2017). Deng, et al. (2013) found critical rotation number on the leading wall as well. They conducted experiments on a U-shaped smooth square passage under high Rotation numbers up to 2.08. The wall temperature was measured by thermocouple. The results revealed that the critical Rotation number was related to dimensionless location parameter X/D, that is, the product of critical Rotation number and corresponding X/D equals constant. Figure 4 illustrates flow profile schematic of U-shaped square smooth passage under different rotation numbers (Deng, et al. 2013). As shown in Figure 4, in first passage (radial outward passage), with Rotation number increasing, separated flow on leading wall is going to occur, which corresponds to a critical Rotation number. When Rotation number is higher than the critical Rotation, separated flow happens, resulting heat transfer near leading wall improved. In second passage (radial inward passage), as Rotation number goes up, separated flow takes place near trailing wall. Qiu, et al. (2013) designed a rotating pressure measurements system to do research on pressure drop and heat transfer in a rotating smooth square U-duct under high rotation numbers. The results indicated that rotation had most dominate effects on the heat transfer performance of the sharp turn due to reinforcing the impingements over the turn. Plus, rotation played a more apparent role on friction ratio when the channel was heated compared to unheated one.

Mayo, et al. (2014) experimentally studied heat transfer distribution of a ribbed rectangular channel under different rotation number and Reynolds number. Steady state liquid crystal thermography was utilized to measure the wall temperature distribution. The Reynolds number was in the range of 15000 to 40000 and the maximum rotation number could be reach 0.12. The result showed that the rotation effect not only played a role on the average heat transfer coefficient value, but also had influence on the heat transfer distribution. Li, et al. (2015) revealed that in rotation state, the heat transfer around trailing side is 4.3 times higher than that around leading side. Fabio, et al. (2016a) and Fabio, et al. (2016b) utilized transient thermochromic liquid crystals to measure the heat transfer coefficient on the trailing wall and leading wall under engine similar conditions with Reynolds number 21000 and rotation number 0.074. The result obtained by Yang, et al. (2017) showed that rotation could restrain the heat transfer performance at the turn part of cooling serpentine passage. Haoliang, et al. (2019) experimentally investigated the Coriolis force on the flow field in a rotational rectangular ribbed channel by using Particle Image Velocimetry (PIV). They found that Coriolis force enlarged the vortex near the leading wall but suppressed the vortex near the trailing wall.

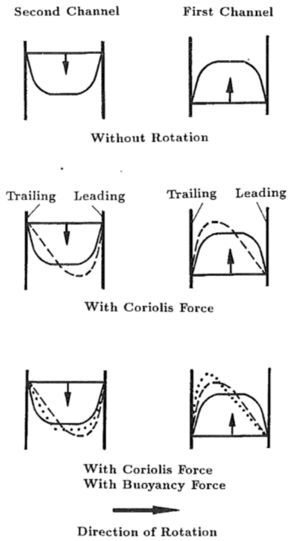

Figure 2 Conceptual view of secondary flow and axial velocity distribution in a U-shaped rectangular smooth passage without heating under rotating condition (Je-Chin, et al. 1993)

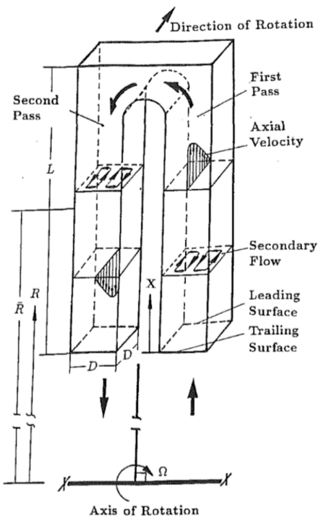

Figure 3 Conceptual view of effect of Coriolis force and buoyance on flow profile (Je-Chin, et al. 1993)

According to the literatures above, it can be concluded that Coriolis force induced by rotation is good for the heat transfer around the trailing wall of radial outward channel and the leading wall of radial inward channel. Plus, under high rotation number condition, there is critical rotation number condition near the leading side of radial outward channel, the product of which and location equals constant. The appearance of critical rotation number may be due to the combined interaction between Coriolis force and normal pressure gradient of coolant. What's more, the technology to measure the heat transfer distribution get great improvement from thermocouple to transient thermochromic liquid crystals. And PIV is an advanced approach to reveal the flow pattern in a rotating cooling channel.

EFFECT OF BUOYANCY

Since rotor blade operates at high temperature condition, heating condition should be considered in the investigation of rotating passage. When rotating cooling channel is heated, uneven coolant temperature distribution leads to buoyance and changes the flow field in the cooling channel. As early as 1950's to 1960's, some scholars (E. R. G. Eckert et al. 1953, Metais , et al. 1964 and Brundrett, et al. 1967) did experimental research to investigate the effect of buoyance. They found that the influence of buoyance is strongly determined by flow direction and that buoyance could significantly change the heat transfer in coolant channel of turbine blade. Figure 3 presents conceptual view of effect of Coriolis force and buoyance on flow profile (Je-Chin, et al. 1993). Based on Figure 3, with buoyance force, the flow distribution in the rotating radial inward channel is more uniform, while the buoyance force enhances the flow around the trailing surface in radial outward channel. In the 1980's, some literatures (Guidez, 1989, Clifford, 1985, Morris, et al. 1979 and W. D. Morris. 1981) about the interaction between Coriolis force and buoyance were carried out, though the conclusions of them were inconsistent.

Parsons, et al. (1994) studied heat transfer coefficient on the trailing wall and leading wall of rotating square U-channel. The result showed that with the increase of buoyance parameter, the heat transfer coefficient on the trailing wall of outflow channel was increased, while that on the leading wall of outflow channel was reduced. Abdel-Wahab, et al. (2004) studied the influence of buoyancy force on the flow field and heat transfer in a ribbed rotating channel by using large eddy simulation. They found that the buoyancy force could accelerate the turbulence near the trailing wall and thus increase heat transfer, but had less effect on the leading wall. Wang, et al. (2017) did theoretical research on the effect of buoyancy on the heat transfer and flow field in a one side ribbed channel under rotating condition. They revealed that the heat transfer and flow field were less affected under non-rotation and very low buoyancy, while significantly influenced under high buoyance. Ruquan, et al. (2017) analysed velocity profile and Reynold shear stress of a four-wall heated radial outward channel by utilizing PIV. They captured separated flow on the leading wall for the first time and considered that buoyance force was the reason causing flow separation. What's more, a leap increase of Reynold shear stress occurred when the flow separation generated. Critical rotation number was observed by Kuan, et al. (2017) as well. They proposed that the critical rotation phenomenon was derived from the interaction between Coriolis force and normal pressure gradient of coolant. Andrea, et al. (2020) experimentally studied the effect of wall heating condition on the heat transfer performance inside a rotation ribbed channel. The found that the heating condition had no effect on the heat transfer distribution under non-rotation condition, while played different roles under rotation condition due to buoyancy effect.

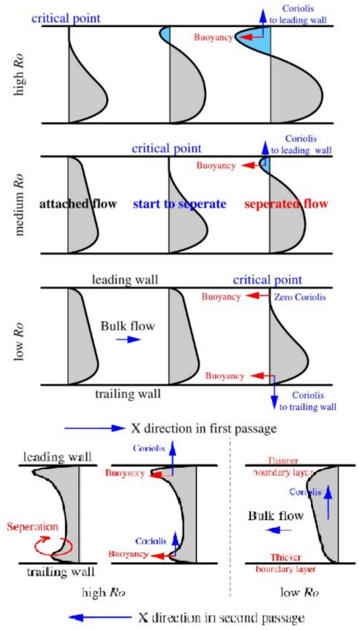

Figure 4 flow profile of U-shaped square smooth passage under different rotation number (Deng, et al. 2013)

Base on the references in this section, buoyancy force has significant effect under rotation, while has less effect under non-rotation condition. Besides, different heating condition plays different roles under rotation condition due to buoyancy effect.

EFFECT OF THE COOLING CHANNEL STRUCTURE

Coriolis force and buoyance force are the main internal causes to affect the flow field distribution and heat transfer performance of blade cooling passage. The structure of cooling channel plays a crucial role on the performance of the passage.

Earlier researcher did more studies on circular cross-section cooling channel to investigate the heat transfer performance of the tube (Morris, et al. 1979 and Metzger, et al. 1977). The concept schematic of cooling channel in rotor blade are depicted in Figure 5 (Yang, et al. 2017). It can be known that the cross section of cooling channels near leading edge can be modelled as rectangular with aspect ratio 1:4 and 1:2, and that the channel near middle part can be simplified as square, and that the channels towards trailing edge can be regarded as rectangular with aspect ratio 2:1 and 4:1 (Yang, et al. 2017). Therefore, increasing scholars pay more attention on rectangular and square smooth passage.

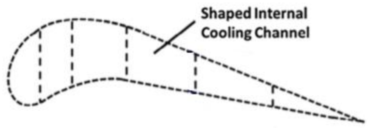

Figure 5 concept schematic of cooling channel in rotor blade (Yang, et al. 2017)

Kuo, et al. (1994) and Soong, et al. (1991) experimentally investigated rotating rectangular tube with aspect ratio 0.5, 1, 2 and 0.2, 0.5, 1, 2, 5 respectively. Their results manifested that the heat transfer performance of cooling channels with different aspect ratio was different and that the channel with aspect ratio 1:1 had the best heat transfer performance. Su, et al. (2004) theoretically predicted the flow field and heat transfer of a U-shaped rotating smooth passage with three different aspect ratio of cross section 1:1, 1:2 and 1:4. They discovered that for the passages with three different aspect ratio, the heat transfer performance was degraded with Reynolds number increasing.

Liu, et al. (2012) experimentally studied a wedge-shaped channel with tapered ribs and lateral flow ejection. This structure of cooling channel is utilized in the trailing edge of rotor blade. The tapered ribs were equipped at leading and trailing walls of the channel. The results showed that though the ribs enhanced heat transfer, the lateral flow ejection played a more domain role on heat transfer distribution. Zhi, et al. (2015) experimentally investigated a rotating wedge-shaped tube with smooth wall and lateral fluid ejection. They provided flow pattern in the tube under non-rotation condition and found large flow separation near the end wall due to the coolant impingement on the end wall. Plus, second flow profile was offered with different channel orientation. The result indicated that the channel orientation was crucial to the wedge-shaped structure, because the horizontal component of Coriolis force exert strong influence on the flow distribution. Since the channel structure of wedge-shaped cross section and lateral fluid ejection has a shortcoming that there is low local heat transfer location at inner part of high-radius half channel, some optimization methods on this structure to improve heat transfer performance have been carried out. Li, et al. (2016) and Yang, et al. (2017) proposed a rotating wedge-shaped cooling channel with two inlets. Compared to conventional wedge-shaped cooling channel with single inlet, they designed an extra inlet around the low heat transfer location to enhance heat transfer of the channel. The results revealed that the heat transfer at high-radius half channel was boosted and that the drawback induced by rotation was compensated. Besides, they found that when mass flow ratio (the ratio of second inlet mass flow to main stream mass flow) was 0.3, the extra second inlet benefited overall heat transfer best under high rotation number condition. Deng, et al. (2021) investigated a rotating channel with film extraction and impingement cooling structure. The result illustrates that this structure can enhance the heat transfer performance of pressure side, while decrease that of suction side.

Ajay, et al. (2019) numerically studied a four-passage serpentine channel based on the profile of blade curvature. The result indicted that heat transfer abilities under rotation and nonrotation conditions were similar and the Coriolis effect under rotating condition can be negated. Bharath, et al (2017) analysed the effect of rib arrangement on the heat transfer and flow characteristic of cooling channel. They found V-shaped rib arrangement offered maximum heat transfer improvement in straight channel part. Willet, et al (2002) studied a rotating cooling channel with pin-fin structure. The result presented that pin fin reduced rotation effect on the channel. I-Lun C. et al. (2020) experimentally studied rotating cooling U channel with staggered discrete V-type ribs. The U channel had inflow channel with aspect ratio 4:1 and outflow channel with aspect ratio 2:1. They concluded that the U channel with staggered discrete V-type ribs had better heat transfer performance than U channel with traditional V-type ribs.

Izzet, et al. (2020) investigated the pressure drop and heat transfer of a converging channel under rotation condition. The result showed that the convergence improved the heat transfer performance of leading wall and trailing wall.

From the article cited in this section, the investigation on the structure of rotating cooling internal channel mainly focuses on channel cross section with different aspect ratio rectangular and wedge-shaped. The mainly reason is that the internal cooing channel with these cross sections can fit the traditional gas turbine blade shape well.

NOVEL DEVELOPMENT TREND OF COOLING CHANNEL FOR GAS TURBINE

Though nowadays traditional serpentine cooling channel is widely used in turbine blade, the Coriolis force due to rotation still induces low heat transfer distribution on leading wall of inflow channel and trailing wall of outflow channel. To obtain higher rotor turbine inlet temperature, and achieve better heat transfer performance on leading and trailing wall, many scholars (Murray, et al. 2020, Sergiy, et al. 2017 and Jason, et al. 2017) proposed "double wall" concept, that is, a structure with thinner wall thickness compared to conventional blade wall. With thinner wall thickness, double wall blade can improve the heat transfer efficiency between coolant and hot gas due to lower thermal resistance. Therefore, in this section, a change orientation inner cooling channel which is turning 90° compared to the conventional cooling channel suitable for double wall design is theoretically analysed. Heat transfer performance of two different change orientation inner cooling channel structures is compared with traditional cooling U channel under the same rotation number condition.

Figure 6 depicts concept geometry of the conventional cooling U-channel and change orientation cooling channels in a rotor blade. In figure 6, red arrow indicates the flow direction of cooling air.

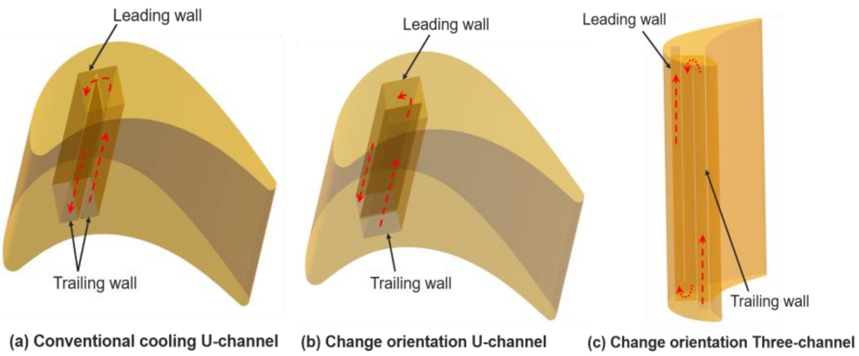

Figure 6 Concept geometry of internal cooling channel in a rotor blade

Figure 7 shows the comparison of regional averaged Nusselt number ratio among the conventional cooling channel and two change orientation cooling channels.

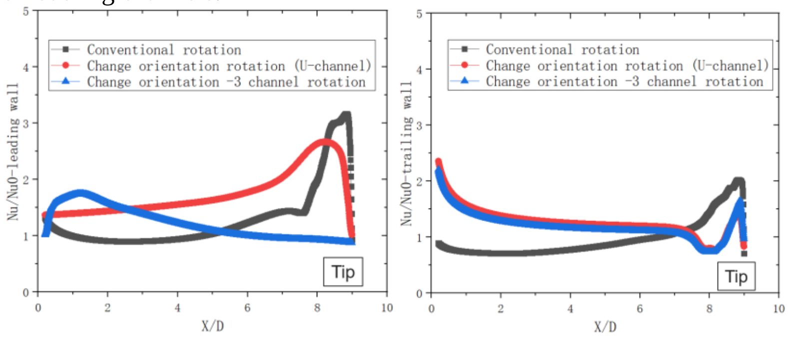

Figure 7 Comparison of regional averaged Nusselt number ratio

According to the left graph of figure 7, the heat transfer performance of the change orientation cooling U-channel on the leading wall is better than that of conventional cooling U-channel and change orientation-three channel. The reason is that the direction of Coriolis force is pointed to the leading wall in the change orientation cooling U-channel and thus enhances the turbulent kinetic energy and heat transfer performance near the leading wall. Based on the right graph of figure 7, the change orientation cooling U-channel and change orientation-three channel shows similar heat transfer performance on the trailing wall. When X/D is lower than 7, the change orientation cooling U-channel and change orientation-three channel performance higher heat transfer ability than the conventional cooling U-channel. When X/D is in the range of 7 to 8.5, the heat transfer performance of the conventional cooling U-channel is higher than that of the change orientation cooling U-channel and change orientation-three channel, where flow separation happened. Though the value of Nu/ Nu0 of change orientation cooling U-channel is lower than the conventional rotation in the area of tip, the area of the tip part is significantly smaller than that of the straight channel part. Therefore, the overall heat transfer ability of the change orientation cooling U-channel is improved compared to the conventional rotation. What' more, the change orientation cooling U-channel is a concept novel design, since it has not applied in the existing blade but it possesses better overall heat transfer ability and has promising application prospect in the novel configuration of future blade, such as double wall cooling blade.

CONCLUSIONS

In the paper, the research status of rotor blade internal cooling is reviewed by classified relevant literatures. The effect of rotation, buoyance force, cooling channel structure on the rotating internal cooling channel is illustrated. Moreover, novel structure design concepts of double wall cooling are introduced and numerically investigated as well.

(1) Coriolis force induced by rotation is good for the heat transfer around the trailing wall of radial outward channel and the leading wall of radial inward channel. Under high rotation number condition, there is critical rotation number condition near the leading side of radial outward channel, the product of which and location equals constant. The appearance of critical rotation number may be due to the combined interaction between Coriolis force and normal pressure gradient of coolant.

(2) Buoyance force uniforms the flow distribution in the rotating radial inward channel, while enhances the flow around the trailing surface in radial outward channel. Besides, buoyancy force has significant effect under rotation, while has less effect under non-rotation condition.

(3) The structure of blade internal cooling passage can be simplified to rectangular, square and wedge-shaped cross-section channel according to the shape of rotor blade. Channel The mainly reason is that the internal cooing channel with these cross sections can fit the traditional gas turbine blade shape well.

(4) Novel cooling channel for double wall blade is numerically investigated. The results indicate that change orientation cooling channels present better overall heat transfer performance than conventional cooling channel on both trailing wall and leading wall. Thus, the change orientation cooling channel is promising in future rotating cooling blade design.

ACKNOWLEDGMENTS

This work is financially supported by National Science and Technology Major Project (2017-III-0009-0035), and Tsinghua University Initiative Scientific Research Program.

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