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Effects of the swirling coolant jet from the upstream slot on the vane endwall cooling and the vane suction side phantom cooling

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ABSTRACT

In order to obtain a higher thermal efficiency, the inlet temperature of gas turbines is gradually increased. However, this increases the thermal load on the first stage vane endwall surface. Therefore, an advanced cooling technique must be implemented for the endwall cooling to ensure that the gas turbine operates safely. In the current study, effects of swirling coolant flow from the upstream slot on the endwall cooling and vane suction side surface phantom cooling were numerically investigated on basis of a validated numerical method. Three-dimensional (3D) Reynolds-averaged Navier–Stokes (RANS) equations combined with the shear stress transport (SST) $k-\omega$ turbulence model were solved in the numerical simulations. The results indicate that the endwall cooling and the phantom cooling are significantly influenced by introducing a swirling coolant jet from the upstream slot relative to the baseline. Compared with the baseline case and the negative swirling coolant jet angle, the positive swirling coolant jet angle contributes to increase the overall uniformity of the endwall cooling effectiveness and reduce the hot region along the pressure side, especially for the case with $\alpha = 20°$. However, it obtains a relatively low level of the phantom cooling effectiveness on the vane suction side. In contrast, the negative swirling coolant jet angle attains a higher level of phantom cooling effectiveness on the vane suction side relative to the positive swirling coolant jet angle. The case with $\alpha = -20°$ obtains the largest phantom cooling effectiveness on the vane suction side. In addition, the aerodynamic loss is increased within a small range. The largest total pressure loss coefficient is 5% for the case with $\alpha = -30°$ among all investigated cases.

1. Introduction

The tremendous increase in the energy demand all over the world and strict regulations on NOx emission must be taken into account and balanced as huge challenges for gas turbine designers. The inlet temperature in modern turbines is increased gradually to pursue a higher level of thermal efficiency. However, the advanced combustor is designed to generate a flat pattern temperature distribution to decrease the NOx production from the combustor. As a result, the temperature near the endwall is significantly increased and hence advanced cooling technologies are urgently required to be implemented in the first stage vane endwall joint to the combustor outlet to reduce the thermal load. In fact, this region is actually difficult to cool due to the influence of the intensified turbulent flow from the combustor and complex secondary flow. In the worst case, severe thermal failures can occur [1].

Film cooling, as an effective cooling technique, has been widely applied to hot components in gas turbines. Many studies concerning the film cooling performance in a gas turbine system have been conducted. Several comprehensive reviews concerning the platform and endwall heat transfer and cooling technologies have been released by Han et al. [2], Simon and Piggush [3]. Bunker [4] published a review regarding shaped hole film cooling performance in a gas turbine. He concluded that many factors affected the endwall cooling performance. However, the geometric parameters had a significant influence on the endwall cooling effectiveness. Barigozzi et al. [5] investigated the effects of the fan-shaped film holes on the aero-thermal performance of a film-cooled endwall. The results indicated that the fan-shaped hole showed better performance than conventional cylindrical film hole. The experiment by Gao et al. [6] showed that shaped holes presented a higher cooling effectiveness and wider coolant coverage on the blade platform than cylindrical holes, particularly at higher blowing ratios.

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Nomenclature

d	diameter of film hole
h	height of vane
$\dot{m}$	mass flow rate
R	nominal radius of the slot injection film hole
T	temperature
T_∞	mainstream temperature
T_{aw}	adiabatic wall temperature
T_c	coolant temperature
x	lateral coordinate
y	vertical coordinate
z	direction along the axial chord length
y^+	dimensionless wall-normal height of first cell at wall
V	velocity

Greek

α	coolant jet angle from the upstream slot film hole
θ	non-dimensional temperature
ζ	total pressure loss coefficient
$\bar{\zeta}$	laterally-averaged total pressure loss coefficient
$\bar{\bar{\zeta}}$	area-averaged total pressure loss coefficient
η	adiabatic cooling effectiveness
$\bar{\eta}$	laterally averaged adiabatic cooling effectiveness
$\bar{\bar{\eta}}$	area-averaged adiabatic cooling effectiveness

Subscripts

a	angular direction
aw	adiabatic wall condition
c	coolant conditions
in	inlet condition
o	total condition
r	angular direction
t	translation direction
∞	mainstream conditions

Chowdhury et al. [7] combined the slash-face and film holes to cool the turbine endwall surface. The cooling effectiveness was significantly increased when the coolant mass flow rate was increased. For the slash-face, the coolant coming out of the upstream portion moved towards the pressure side, resulting in an increase in the pressure side endwall cooling effectiveness.

In a real gas turbine, there are many inevitable interfaces between different parts because the engine is assembled with different components. Consequently, coolant flow can be provided from the interfaces to prevent the hot gas ingestion and cool the hot parts. One of the most important interfaces is the upstream slot between the combustor outlet and turbine inlet. This can be utilized to supply the coolant to protect the downstream first stage vane endwall surface. Blair [8] firstly found that the film coolant injection from the upstream slot reduced heat transfer and also had a significant influence on the passage flow. Moreover, he concluded that the upstream slot and coolant injection both promoted transition within the boundary layer. The experiment by Burd et al. [9] showed that the case with upstream slot coolant jet obtained an overall 6% higher cooling effectiveness level than the case without the upstream slot coolant jet. Pasinato et al. [10] stated that the coolant jet from the upstream slot was driven by the lateral pressure difference towards the vane suction side. The local heat transfer coefficients near the leading edge were reduced relative to the case without slot coolant jet. Nicklas et al. [11] indicated that the horseshoe vortex was enhanced significantly without the film hole coolant injection due to the upstream slot coolant alone being easily lifted off the endwall surface. In addition, Knost et al. [12] found that the variation of the pressure at the upstream slot outlet resulted in a non-uniform coolant distribution. Then it led to a large uncooled region around the leading edge and along the vane pressure side. Lynch and Thole [13] conducted experiments to investigate the heat transfer and cooling performance on a contoured blade endwall with platform gap leakage. They found that the endwall coolant coverage was limited by the horseshoe vortex. However, increasing the gap coolant leakage resulted in the enhancement in the cooling effectiveness around the plat form gap.

Many studies also have been conducted concerning the influence of the cooling configuration on the cooling effectiveness enhancement of the endwall. Cardwell et al. [14,15] stated that the coolant coverage can be significantly increased by decreasing the width of the upstream slot. This contributed to the uniform distribution of the coolant because of the enhancement of the coolant injection momentum. Moreover, the experiments showed that the endwall alignment could significantly increase the cooling effectiveness when the pressure side endwall was higher than the suction side endwall. Du et al. [16,17] implemented the filleted upstream slot and leading edge injection slot in a linear cascade. The results indicated that the filleted upstream slot made great contribution to increasing the cooling effectiveness of the endwall due to the decrease of the coolant lateral migration compared to the conventional upstream slot. Furthermore, the cooling effectiveness near the leading edge-endwall was significantly enhanced by introducing the leading edge injection slot. This is because the coolant jet from the leading edge injection slot is driven towards the upstream endwall by the assistance of the vertical flow near the leading edge-endwall junction. Some studies [18,19,20] concerned the effects of the upstream slot coolant injection angle and the upstream geometry on the endwall cooling effectiveness. The upstream slot coolant injection angle has a significant influence on the endwall cooling effectiveness, especially near the pressure side endwall surface. Moreover, the coolant distribution can be rearranged by introducing a contoured upstream slot. Consequently, the downstream endwall obtains an enhancement of the cooling effectiveness because the coolant leakage at the slot outlet becomes more uniform.

In order to enhance the cooling effectiveness, the swirling coolant flow has also been implemented in gas turbine cooling systems to enhance the cooling effectiveness of the endwall surface. Takeishi et al. [21] conducted the experiment to investigate the influence of the swirling coolant flow on cooling effectiveness the first nozzle endwall surface. The results indicated that the cooling effectiveness of the nozzle endwall was significantly enhanced by introducing the swirling coolant flow relative to the conventional case. Li et al. [22] investigated the cooling performance of the turbine endwall surface and the phantom cooling on the suction side surface by experimental and numerical methods. The results showed that the endwall cooling effectiveness could be increased at a suitable swirling ratio, however, the corresponding phantom cooling effectiveness was decreased.

Phantom cooling was earliest investigated by Roback and Dring [23,24] concerning the phantom cooling measurements in a one and half stage rotating turbine stage by using the gas chromatography method. Zhang et al. [25] expanded the phantom cooling definition and investigated the influences of the vane showerhead