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Effects of the cooling configurations layout near the first-stage vane leading edge on the endwall cooling and phantom cooling of the vane suction side surface

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ABSTRACT

Increasing the turbine inlet temperature can enhance the thermal efficiency of a gas turbine. Therefore, modern gas turbines operate at a relatively high level of temperature and endure heavy thermal load. It is important to ensure the modern gas turbine works at a high performance and safe condition. Advanced cooling techniques are implemented in the gas turbine system. In the current study, effects of the cooling configurations layout near the first-stage vane leading edge on the endwall cooling and phantom cooling of the vane suction side surface were numerically investigated. Three-dimensional (3D) Reynolds-averaged Navier-Stokes (RANS) equations combined with the shear stress transport (SST) $k-\omega$ turbulence model were solved to perform the simulations on basis of validation by comparing the experimental data and computational results. The results indicate that the layout of the cooling configurations has a significant influence on the endwall cooling, but a limited effect on the phantom cooling of the suction side surface and the aerodynamic performance. For each type, the endwall cooling and phantom cooling of the suction side surface are enhanced with the increase of the blowing ratio (M) of the leading edge coolant injection. Meanwhile, the thermodynamic loss is gradually enhanced. Overall, the Type B which has a partly blocked upstream slot achieves the best performance in terms of the coolant mass flowrate, endwall cooling, phantom cooling performance of the suction side surface and the aerodynamic performance at $M = 1.0$.

1. Introduction

Increasing the turbine inlet temperature is regarded as an effective method to enhance the thermal efficiency of the gas turbine. However, the environment regulations claim to decrease NOx emission. Therefore, a flat pattern of temperature distribution at the combustor outlet is urgently requested to minimize the NOx at a relative high thermal efficiency. In general, modern gas turbines operate at a high level of inlet temperature. Consequently, the first stage vane endwall is subject to an extremely high level of thermal load due to the intensified vertical flow. As a result, the advanced cooling schemes are implemented in this region together to enhance the cooling effectiveness for the hot component.

The endwall flow-field of a first stage turbine vane incorporates the impingement of the hot gas and the intensified vertical flow that result in high heat transfer and aerodynamic losses. Langston [1], Goldstein and Spores [2], and Sharma and Butler [3], Simpson [4] conducted several studies concerning the heat transfer and aerodynamic losses in a first stage turbine vane. They concluded that a horseshoe vortex was generated at the upstream region of the passage by a combination of slow boundary layer flow and the main flow encountering the vane endwall junction. Then the horseshoe vortex splits into suction side and pressure side legs. Moreover, the pressure side leg of the horseshoe vortex develops into a passage vortex at downstream region, which has a significant influence on the flow structure in the passage. As a result, the passage vortex lifts a portion of the coolant off the endwall surface, resulting in an increase of the endwall thermal load.

Film cooling, as an effective cooling method, has been widely used in gas turbine systems. Han et al. [5], Simon and Piggush [6] published several reviews regarding the platform heat transfer

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Nomenclature

D	diameter of film hole
h	height of vane
$\dot{m}$	mass flowrate
Ω	vorticity
R	radius of the fillet at the slot downstream edge
T	temperature
T_∞	mainstream temperature
T_{aw}	adiabatic wall temperature
T_c	coolant temperature
μ_τ	friction velocity
v	fluctuating velocity
V	velocity
w	upstream slot width
W	non-dimensional upstream slot width $W = \frac{w}{D}$
x	lateral coordinate
X	non-dimensional lateral coordinate $X = \frac{x}{D}$
y	vertical coordinate
Y	non-dimensional vertical coordinate $Y = \frac{y}{D}$
z	stream-wise coordinate
Z	non-dimensional stream-wise coordinate $Z = \frac{z}{D}$
y^+	dimensionless wall-normal height of first cell at wall

Greek

α	slot injection angle
θ	non-dimensional temperature $\theta = (T - T_c)/(T_\infty - T_c)$
ρ	density
ζ	thermodynamic loss coefficient
η	adiabatic film cooling effectiveness
$\bar{\eta}$	laterally averaged film cooling effectiveness
$\bar{\bar{\eta}}$	area-averaged film cooling effectiveness
τ	shear stress
μ	dynamic viscosity

Subscripts

0	stagnation condition
1	upstream condition
2	downstream condition
aw	adiabatic wall condition
c	coolant conditions
in	inlet condition
outlet	outlet condition
rms	root-mean-square
s	static condition
∞	mainstream conditions
x	lateral coordinate component
w	wall condition

and cooling techniques. Bunker [7,8] presented detailed reviews and indicated that the shape of the film hole was of great importance to improve the cooling performance. Moreover, he indicated that the trenched film holes achieved an enhanced film cooling effectiveness level relative to cylindrical holes. Gritsch et al. [9] experimentally found that the fan-shaped hole achieved superior cooling performance to the cylindrical film hole due to the enhancement in lateral diffusion of the coolant, especially at a high blowing ratio. Kianpour et al. [10] concluded that trenching cooling holes had the superior film cooling performance at higher blowing ratios by measuring the film effectiveness of cylindrical and row trenched cooling holes. Wang et al. [11,12] also investigated the influence of the height, width and locations of the deposition on the endwall film cooling. They stated that the deposition resulted in a significant decrease of film cooling effectiveness.

Many leakage gaps are inevitable in a gas turbine system. This is because a gas turbine is assembled with different components. The upstream slot is one of the leakage gaps, it is generated between the combustor outlet and the turbine inlet. In order to obtain a high cooling effectiveness level, the upstream slot was utilized to enhance the cooling performance of the endwall surface. Lynch et al. [13] compared the heat transfer and film cooling performance between the cases with injection and without slot coolant injection. They indicated that the film cooling effectiveness was significantly enhanced by introducing slot coolant injection. Furthermore, the heat transfer coefficients were also slightly increased with the introduction of the slot coolant injection. Studies by Cardwell et al. [14,15] indicated that the hot regions can be significantly reduced by decreasing the upstream slot width. This is because the coolant from a small width of the slot obtains uniformly spreading due to the increased momentum of the coolant injection to reduce the influence of the non-uniform pressure distribution along the upstream slot outlet. Moreover, endwall alignment has a significant effect on the endwall film cooling performance. A significant increase of the film cooling effectiveness can be observed when the pressure side endwall is higher than the suction side endwall of the adjacent vane. Thomas et al. [16] proposed a new design method for cooling of high-pressure nozzle guide vane endwalls. The design of the momentum distribution of the cooling jets must be combined with total pressure profile to control vane lateral migration thereby improving endwall cooling uniformity.

For pursuing a higher cooling effectiveness level, many researchers investigated the cooling performance of the endwall surface by combining the upstream slot and the film-hole cooling near the leading edge. Early experiments by Nicklas et al. [17] combining an upstream slot with film holes stated that a higher adiabatic cooling effectiveness level was observed at the suction side endwall surface than the pressure side endwall surface as a result of the lateral migration of the slot coolant. Furthermore, they stated that the slot coolant enhanced the horseshoe vortex, which lifted the coolant off the endwall surface, resulting in an increase of the heat transfer coefficients on the downstream endwall surface. Knost et al. [18] and Thole et al. [19,20] indicated that the upstream slot enhanced the endwall cooling effectiveness at a large region of the endwall surface. However, the non-uniformly of coolant was generated at the outlet of the upstream slot. This was because variation of the pressure distribution at the upstream slot outlet. Consequently, the coolant was forced towards the vane suction side, inducing a large uncooled region along the pressure side and around the leading edge. Du and Li [21] found that the coolant separation was significantly reduced by introducing a filleted upstream slot. Consequently, a higher cooling effectiveness level on the endwall surface, especially around the leading edge was achieved for the filleted upstream slot compared to the sharp-edged slot. In addition, Schobeiri et al. [22] investigated the effects of the non-axisymmetric contouring on the endwall cooling performance. The results showed that the non-axisymmetric contouring can enhance the film cooling effectiveness on the endwall, Moreover, the mass flowrate of the coolant injection and the rotating speed of the rotor have significant influence on the ednwall cooling effectiveness.