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Effects of upstream slot geometry on the endwall aerothermal performance of a gas turbine blade under different ejection angle conditions

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ABSTRACT

In the current study, effects of upstream slot geometry with different ejection angles on endwall flow and heat transfer characteristics of a gas turbine blade are numerically investigated. Based on validation of the numerical method, the Reynolds-averaged Navier-Stokes (RANS) equations combined with the standard k-ω turbulence model are adopted in this study. The effects of convergent and divergent slot geometries on near-endwall flow structure and endwall heat transfer behavior are studied when ejection angles are 45 deg and 90 deg respectively. The results indicate that compared with a normal slot, the convergent slot significantly improves the endwall cooling performance when the ejection angle is 45 deg, so the thermal loads on the endwall are remarkably reduced. Moreover, the convergent slot can also decrease the aerodynamic losses in blade passage when the coolant to main flow mass flow ratio is higher than 1.0%. However, when the ejection angle is 90 deg, the advantage of the convergent slot in endwall cooling does not exist and heat transfer on the fore part of the endwall is increased by the convergent slot. Consequently the thermal loads on the fore part of the endwall are enhanced, especially, when mass flow ratio reaches 1.5%, the thermal loads on the endwall near the leading edge are increased by 28% compared with that for the normal slot. Besides, the convergent slot also increases the aerodynamic losses when the ejection angle is 90 deg. As to the divergent slot, it has an adverse effect on cooling protection for the endwall with both ejection angles and its effects on both cooling protection and aerodynamic performance are much less than those for the convergent slot.

1. Introduction

Gas turbines have many important applications in energy and power fields such as aircraft propulsion, ship power and land-based power generation [1]. Increasing turbine inlet temperatures is a key technology to improve thermal efficiency and power output of gas turbines. The turbine inlet temperatures in advanced gas turbines are far beyond melting point of turbine component materials. Therefore, modern cooling technology plays a very important role in safe, reliable and efficient operation of gas turbines. In addition, due to flatter turbine inlet temperature profiles and higher thermal loads on the endwall, cooling demands of the endwall in modern gas turbines is increased [2].

The presence of complicated secondary flow structures near the endwall increases the difficulty of cooling protection for the endwall. Goldstein et al. [3] and Langston [4] described the secondary flow structures in blade passage. In most studies, horseshoe vortex, passage vortex and endwall cross flow are considered as dominant secondary flow structures. The experimental results of Maclasaac et al. [5] showed that the passage vortex forced the low energy fluid into low loss region near the endwall. The experiment of Knezevici et al. [6] indicated that a reduction of the endwall cross flow could decrease the passage vortex intensity.

These complicated secondary flow structures have a critical effect on heat transfer characteristic of the endwall. Radomsky and Thole [7] experimentally demonstrated that secondary flow structures could significantly enhance heat transfer on the endwall. The experiment of Han and Goldstein [8] indicated that a modified blade with a fillet geometry reduced secondary vortices such as the horseshoe vortex and passage vortex to decrease heat transfer on the endwall. Lynch et al. [9,10] experimentally and numerically studied the influence of nonaxisymmetric endwall contouring on heat transfer of a highly loaded gas turbine blade. The results indicated that the heat transfer intensity is reduced by 20% due to a reduction of the passage vortex by the

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Nomenclature

C	chord length of blade, mm
C_{ax}	axial chord of blade, mm
P	blade Pitch, mm
S	blade span, mm
D	distance between slot and blade, mm
W	slot width, mm
L	slot length, mm
Re_{outlet}	outlet Reynolds number based on blade passage outlet velocity and blade chord
q_w	wall heat flux, W/m^2
h	heat transfer coefficient, W/(m^2 K)
MFR	mass flow ratio of purge flow to mainstream flow
M	blowing ratio of purge flow, $(\rho_c U_c/\rho_\infty U_\infty)$
T_∞	inlet temperature of mainstream, K
T_c	inlet temperature of purge flow, K
T_{aw}	adiabatic wall temperature, K
T_w	wall temperature, K
Nu	Nusselt number
$NHFR$	Net heat flux reduction
m	mass flow rate, kg/s
p_t	total pressure, Pa
U	velocity

Greek letter

α	ejection angle of slot, deg
η	film cooling effectiveness
λ	fluid thermal conductivity, W/(m K)
ρ	fluid density, kg/m^2
ϕ	non-dimensional temperature, $(T_\infty - T_{aw})/(T_\infty - T_c)$
μ_T	turbulent viscosity, kg/(m s)
μ_L	laminar viscosity, kg/(m s)
$\bar{\xi}_{p,t}$	total pressure loss coefficient
ξ_{local}	local total pressure loss coefficient, $(P_{t,\infty} - P_t)/0.5\rho_\infty U_\infty^2$
Ω	streamwise vorticity, s^{-1}

Subscripts

aw	adiabatic wall
w	wall
c	coolant
∞	freestream
out	blade passage outlet

nonaxisymmetric endwall contouring. Papa et al. [11] claimed that the horseshoe vortex significantly augmented heat transfer near the blade leading edge and the vortex shedding was responsible for the high heat transfer level near the trailing edge.

In modern high pressure gas turbines, in order to ensure safety and reliability of components in disk cavities, some cooling air bled from the compressor is ejected from the hub gap to prevent the high temperature mainstream gas from ingesting into the disk cavities. The mechanism of mainstream flow ingestion and flow and heat transfer characteristics in the disk cavities have been extensively investigated [12,13]. In recent years, an significant effect of coolant ejection from the upstream slot on aerothermal performance of the endwall are recognized. The experimental and computational results of Schüpbach et al. [14] indicated that a critical influence of the purge flow on the secondary flow structures directly affected the aerodynamic performance of the blade endwall. Hence during the design process of endwall the effect of purge flow must be taken into account. The experiment results of Regina et al. [15] showed that aerodynamic efficiency of turbine stage was reduced by 0.8% with per percent of mass flow rate of purge flow. Rehder et al. [16] claimed that the enhancement of the horseshoe vortex strength by the perpendicular coolant ejection from the upstream slot led to heat transfer augmentation near the blade leading edge. Lynch and Thole [17,18] demonstrated that the coolant ejection from the upstream slot significantly enhanced the heat transfer intensity on region between the slot and the blade leading edge.

Moreover, the coolant ejection from the upstream slot has an ability of cooling the endwall. Thole et al. [19,20] experimentally investigated the effect of purge flow from the interface between combustor and turbine on the film cooling effectiveness of the endwall. The results indicated that the coolant ejection from the upstream slot provided film cooling for the fore part of the endwall. The experiment of Cardwell et al. [21] showed that the mass flow rate of the purge flow from the upstream slot significantly influenced the level of film cooling effectiveness of the endwall and as the mass flow rate of purge flow increased the endwall film cooling effectiveness was increased. The momentum flux of the purge flow influenced the area covered by the coolant ejection and with momentum of the purge flow increasing the coverage area was increased. The injection configuration and endwall alignment were numerically investigated by Du and Li [22]. The results indicated that the filleted slot could improve the film cooling effectiveness of the endwall.

For the case of a high-performance blade with a high turning angle, limited studies about effects of coolant ejection from the upstream slot on flow and heat transfer characteristics on the endwall are available [2,23–25]. Due to a strong transverse pressure gradient between the pressure and suction sides in the blade passage with the high turning angle, the influence of secondary flow structures on the aerothermal performance are much greater. Papa et al. [2] experimentally demonstrated that a higher blowing ratio of coolant ejection from the upstream slot could enhance the ability of coolant overcoming the secondary flow and improve the cooling performance of the coolant ejection. Effects of swirling angle of the purge flow on flow and heat transfer characteristics of the endwall were experimentally investigated by Barigozzi et al. [23]. The results indicated that when the mass flow of the purge flow was higher, a negative swirling angle significantly enhanced the passage vortex which increased the aerodynamic losses and reduced the endwall film cooling effectiveness. Li et al. [24] considered both effects of mainstream turbulence intensity and swirling ratio. They experimentally demonstrated that when the mainstream turbulence intensity equaled 13%, the purge flow could provide the greatest film cooling for the endwall. Song and Zhu et al. [25] numerically investigated the effect of ejection angle of slot on aerothermal performance of the endwall. Their results indicated that as the ejection angle increasing, the film cooling effectiveness on the endwall was increased and the aerodynamic losses were reduced. The most of these studies are concentrated on flow parameters of the coolant ejection from the upstream slot and the studies of slot geometrical parameters are limited. In this study, two novel slot geometries including convergent and divergent slots are considered. The effects of these two slot geometries on the secondary flow structures, endwall film cooling effectiveness, heat transfer performance and aerodynamic losses are numerically investigated under different ejection angles.