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An experimental investigation of geometric effect of upstream converging slot-hole on end-wall film cooling and secondary vortex characteristics

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ABSTRACT

A row of converging slot-holes is applied upstream of a linear GE-E^3 high pressure turbine cascade to enhance film-cooling effect in end-wall leading edge region and weaken secondary vortices. Effects of geometric parameters of the converging hole-slot, including inclination angle and outlet-to-inlet area ratio, on time-mean characteristics of secondary vortices and adiabatic film-cooling effectiveness are respectively investigated with Time-Resolved Particle Image Velocimetry (TRPIV) and Planar Laser Induced Fluorescence (PLIF) techniques, at various coolant-to-mainstream blowing ratios. Three types of converging slot-holes with two different area ratios (ARs = 1.38 and 0.69) and inclination angles ($\alpha = 30°$ and 65°) are chosen, and a 30° cylindrical hole is compared as a reference. The comparison reveals that, the secondary vortices can be weakened by the coolant injection from the cylindrical hole only at higher blowing ratios; however, the 30° converging slot-holes has a potential to simultaneously improve end-wall cooling effect and weaken the secondary vortices, even at lower blowing ratios. For the two 30° converging slot-holes, the configuration with smaller AR = 0.69 is a better structure, because that can provide a better film-coverage performance, a higher film cooling effectiveness, and a stronger ability to weaken secondary vortices, compared to larger AR = 1.38. For the 65° converging slot-holes, the coolant lifts easily off the end-wall, and the secondary vortices are enhanced by the coolant injection. Therefore, this configuration is not suitable for weakening the secondary vortices.

1. Introduction

In a gas turbine cascade, as high temperature fluid stagnates onto leading edge (LE) of vanes or blades, a roll-up horseshoe vortex (HV) is generated by a span-wise static pressure gradient at the junction of an end-wall with the LE. Then, the LEHV splits into two parts along pressure side (PS) and suction side (SS) of the vanes or blades, and the two horseshoe vortices merge in a complicated way to form a large passage vortex (PV). These secondary vortices can cause a large aerodynamic loss and a high convective heat transfer coefficient at end-wall [1–4]. Therefore, control of LEHV and PV is deemed to be an effective approach to improve the performances of turbine cascade.

Currently, with a rapid increase of turbine inlet temperature, film cooling has been widely chosen to maintain the reliability of end-wall, which is subjected to a severe thermal environment [5,6]. Highest heat transfer rate at the end-wall is generated in the end-wall LE region, due to the formation of LEHV [7]. However, Friedrichs et al. [8] indicated that the end-wall LE is the most difficult region to be cooled, since the LEHV can easily lift the coolant off the surface. In previous investigations [9–24], the interface slots of combustor-turbine or rotor–stator were generally used to provide essential coolant to protect the end-wall LE region. The experimental results provided by the research group of Professor Karen Thole [9–14] indicated that, a reduction of the injection angle of slot from 90° to 45° can provide as much as 137% reduction of the heat load averaged over the end-wall; and LEHV can be removed away from the end-wall at the high momentum coolant injection from 45° and 30° slots, while LEHV is enlarged by 65° and 90° injections. The experimental results of Rehder and Dannhauer [19] showed that coolant injection at tangential angle can reduce the strength of HV and PV, even remove HV at higher coolant flow rates; whereas coolant injection at perpendicular angle can strengthen HV and PV. Therefore, with the studies mentioned above as a background, it can be concluded that

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Nomenclature

c	scaled-up chord length, m
C_{xy}	time-mean velocity contour in plane $x-y=sqrt(U^2+V^2)$, m/s
D	inlet diameter of film-cooling holes, m
TC	local tracer concentration, mg/L
U_c	mean velocity at inlet of film-cooling hole, m/s
U_{in}	inlet mean velocity of blade passage, m/s
U	time-mean velocity in the x direction, m/s
V	time-mean velocity in the y direction, m/s
x, y	in-plane coordinates of measurement planes
z	out-of-plane coordinate of measurement planes
ω_z	time-mean out-of-plane vorticity contour, 1/s
ρ_c	density of coolant
ρ_{in}	density of mainstream
α	inclination angle
θ	local dimensionless coolant concentration
η	end-wall film-cooling effectiveness

Acronyms

AR	area ratio of outlet-to-inlet
BR	blowing ratio of coolant-to-mainstream, i.e. $BR=(\rho_c U_c)/(\rho_{in} U_{in})$
HV	horseshoe vortex
LE	leading edge
PV	passage vortex
PS	pressure side
SS	suction side
PLIF	planar laser induced fluorescence
TRPIV	time-resolved particle image velocimetry

the coolant injection from upstream slot with suitable geometric parameters can simultaneously weaken the secondary vortices and enhance the end-wall film cooling effectiveness. However, the investigations of Kost and Nicklas [20], Burd et al. [21], Oke et al. [22] and Zhang and Jaiswal [23] indicated that the coolant flow from upstream slot is affected by sophisticated secondary vortices to result in a non-uniform cooling effect at the end-wall, i.e., the end-wall region near SS is cooled, but near PS, cooling effect is slight. Therefore, it is necessary to develop more effective cooling structures using novel discrete holes, placed between the upstream slot and vane/blade LE, to assist to the upstream slot to improve end-wall cooling effectiveness, achieve uniform effectiveness distributions and weaken the secondary vortices. Sundaram and Thole [24] utilized a row of 30° trenched cylindrical-holes installed between a 45° slot and first-stage vanes to cool the end-wall LE junction, and their results revealed that, compared with non-trenched holes, trenched holes can provide a better coolant jet attachment to end-wall, a higher turbulence level near end-wall, a higher vorticity level, and an enhanced adiabatic film effectiveness level thereby.

A novel film-cooling hole named as converging slot-hole was introduced by Sargison et al. [25] in 2002. The structure of converging slot-hole transits from a circular hole into a slot with convergence in axial direction and divergence laterally. Flat plate tests conducted by Sargison et al. [25] showed that, converging slot-hole is a structure with higher cooling effectiveness and lower aerodynamic loss comparing to cylindrical hole; with cooling effectiveness on the same level but lower aerodynamic loss in comparison with fan-shaped hole; and with aerodynamic loss on the same level with slot. Numerical results of Azzi and Jubran [26] and Yao and Zhang [27] using a flat plate model indicated that the interaction between coolant from converging slot-hole and mainstream causes a formation of anti-kidney vortices to suppress the coolant off the wall. In recent years, converging slot-hole has been applied to cool the vane or blade surface by Liu et al. [28] and Yao et al. [29], and their results indicated that converging slot-hole can provide higher film cooling effectiveness comparing with cylindrical hole.

In our recent work of Pu et al. [30], a cooling method using a row of converging slot-holes was proposed to assist to the upstream slot to cool the end-wall LE region of a linear GE-E^3 high pressure turbine cascade. However, to understand individually the influence of coolant injection from converging slot-hole on the characteristics of secondary vortex and end-wall film-cooling, the slot upstream of the converging slot-hole was not considered. Inclination angle (α) and outlet-to-inlet area ratio (AR) of this type of converging slot-hole is 30° and 1.38, respectively. Our experimental results using TRPIV technique indicated that, the coolant injection from the converging hole-slot is propitious to suppress formation of LEHV, even at a low blowing ratio (BR) of 0.5; and a high BR of 1.5 can greatly weaken PV vorticity and cause LEHV to vanish. In previous study of Takeishi et al. [31], a fan-shaped hole was designed upstream of the cascade to cool the end-wall LE junction and suppress the formation of LEHV, and the results indicated that a suitable distance between film-cooling hole and LE, and a suitable BR can not only decrease the thermal loaded at end-wall, but also weaken the strength of LEHV, while an insufficient BR of 0.5 actually reinforces the growth of LEHV. Therefore, comparing with the fan-shaped hole, the converging slot-hole is highly recommended to weaken the end-wall secondary vortices, at a low momentum injection. However, in our previous work of Pu et al. [30], the influence of geometric parameters of converging slot-hole on the characteristics of end-wall film cooling and secondary vortices in the cascade has not yet been carried out. Actually, according to previous studies of [6,9–14,32,33], fluid flow and film cooling characteristics of discrete film-cooling holes or continuous slots are mainly affected by the geometric parameters (including α and AR) and flow parameters (including BR, Reynolds number and density ratio). Therefore, to optimize the structures of converging slot-hole upstream of the cascade, it is necessary to understand the influences of geometric parameter (including α and AR) on secondary flow characteristics and scalar transport characteristics of coolant at different flow conditions.

Based on our previous study of Pu et al. [30], the current work focuses on discussing the geometric effect of converging slot-hole on the adiabatic film-cooling effectiveness in the end-wall LE region and the characteristics of HV and PV at different BRs from 0.5 to 2.0. To understand individually the geometric influences of converging slot-hole on the characteristics of fluid flow and film cooling, the slot upstream of the converging slot-hole is also not considered in this work. Three types of converging slot-holes with two different ARs (ARs = 1.38 and 0.69) and inclination angles (α = 30° and 65°) are chosen, and a 30° cylindrical hole is used as a comparison. The spatial distributions of coolant concentration are measured by PLIF technique, adiabatic film-cooling effectiveness is calculated through heat-mass transfer analogy, and characteristics of LEHV and PV are captured using TRPIV. The purpose of this work is to understand the influence of the geometric parameters of converging slot-hole on the film cooling effectiveness and secondary flow characteristics, to optimize the structural design of film-cooling hole installed upstream of the cascade, as well as to provide numerical investigators with a relatively comprehensive database to validate numerical methods.