International Journal of Heat and Mass Transfer 123 (2018) 285–296

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Computational investigation of film cooling and secondary flow on turbine endwall with coolant injection from upstream interrupted slot

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ARTICLE INFO

Article history:
Received 6 November 2017
Received in revised form 21 January 2018
Accepted 29 January 2018

Keywords:
Endwall
Interrupted slot
Film cooling
Blowing ratio
Axial position

ABSTRACT

High pressure turbine vane surface and endwall regions are extensively cooled through discrete holes and leakage flow from combustor-turbine interface gap. For making better use of the limited amount of the leakage flow, this paper describes numerical investigation of endwall film cooling performance of a two-dimensional cascade with upstream interrupted slot injection. The geometry of the vane, size of the slot and mainstream parameters are all taken from a real engine high pressure turbine. The effects of varying blowing ratio, location of the upstream slot and coolant incidence angle on cooling effectiveness are studied. The ranges of the studied parameters are: blowing ratio 1.0, 1.7, 1.86; slot location Z/Cax = −0.1, −0.2, −0.3; coolant incidence angle −10°, 10°, 20°. The calculations are completed by solving three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations with shear stress transport (SST) k-ω turbulence model, meanwhile, the turbulence model was validated by comparing the calculated results with the experiment data. The calculated results show an important influence of blowing ratio and axial position of the interrupted slot on film cooling effectiveness. Cooling Effectiveness is increased with increasing blowing ratio and decreasing distance between the slot and leading edge of the vane. To compare with BR = 1.7 cooling effectiveness can be improved significantly in the condition of BR = 1.86. Slot location of Z/Cax = −0.1 provides much higher cooling effectiveness than the rest two locations. The physical mechanism of the improvement is that in the condition of high blowing ratio high momentum coolant flow helps to reduce the strength of horseshoe vortex and therefore to limit its negative effect on the cooling effectiveness. The high momentum coolant jet impinges on leading edge of the vane and climbs the surface of it. The coverage of the coolant at the leading edge endwall and pressure side endwall junction becomes better. The contours of effectiveness for different slot location are similar to those of different blowing ratio. The momentum of the coolant jet increases with the slot moving close to the leading edge of the vane and creates similar effectiveness contour patterns of raising blowing ratio. The effect of varying coolant incidence angle on the cooling effectiveness is weaker than blowing ratio and slot location. Average cooling effectiveness is increased about 14% when the angle changed from 10° to 20°.

1. Introduction

The demand of high performance of modern gas turbine can be achieved by increasing the turbine inlet temperature. With the increasing temperature, specifically, the first stage turbine vane will undergo even much higher thermal load. From the engineering's perspective, one critical region is vane endwall domain. Most of the combustor-turbine mutual junctions always have leakage gap through which coolant flow may leaks into the main gas path inevitably. These junctions, depending on the design and operating conditions, typically consist of either a backward-facing slot, or a forward-facing slot, or even a simple flush slot. Near the endwall region, with the existence of the various kind of slot, hence, the interaction of coolant air and secondary flow plays a crucial role on film cooling effectiveness. Subsequently, to know exactly the film cooling effectiveness and its underlying physical mechanisms near the vane endwall region, investigation of the secondary flow has always been treated as priority. Secondary flow studied by Langston et al. [1], Sharma and Butler [2], Goldstein and Spores [3], and others have already showed that, to some extent, the incoming flow will act as similar flow structure. More specifically, the incoming boundary layer on the endwall rolls up into horseshoe vortex at the leading edge. Then the horseshoe vortex splits

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.117
0017-9310/

Nomenclature

AP1, AP2	axial position of slot
BR	blowing ratio, $BR = \rho_c U_c / \rho_{in} U_{in}$
C	true vane chord
C_{ax}	axial vane chord
C_p	static pressure coefficient, $Cp = (P - P^*_{in})/(0.5 * \rho_{exit} U^2_{exit})$
HSV	horseshoe vortex
IA	coolant incidence angle
Ma	Mach number
P	vane pitch or static pressure
P*	total inlet pressure
Re	Reynolds number, $Re = \rho U_\infty C_{ax}/\mu$
S	vane span height
SB	separation bubble
SV	step vortex
T	static temperature
TV	tertiary vortex
U	streamwise velocity
X	pitchwise direction
Y	spanwise direction
Z	axial direction
η	adiabatic film cooling effectiveness, non-dimensional temperature
μ	viscosity
ρ	density

Subscripts

exit	mainflow outlet
in	mainflow inlet
∞	freestream velocity

Normalized parameter

X/P	non-dimensional pitchwise position
Y/S	non-dimensional spanwise position
Z/Cax	non-dimensional axial position

into suction and pressure side legs, where the pressure side leg develops into a passage vortex. And all these complex vortex structures can be attributed to the formation of the secondary flow within the mainstream flow of the vane passage.

Several past studies have investigated the performance of leakage flows from upstream interface gap on endwall film cooling effectiveness. As it is known by the authors, Blair [4] is the first researcher who investigated the endwall film cooling and found an apparent endwall domain accompanied with the raise of the heat transfer coefficient. He attributed such kind of phenomenon to the strong secondary flow fields at the vanes' suction side corner. Later, Friedrichs et al. [5–7] gave a detailed distribution of the endwall film cooling performance without its upstream slot. The most interesting thing is that even absence of endwall upstream slot, the results indicated a strong interaction between secondary flow and coolant from cooling holes.

Furthermore, some researchers attempt to reveal the effect of the upstream slot on the performance of the endwall cooling effectiveness. For example, Roy et al. [8] performed the experiments and numerical simulations to determine the convective heat transfer distribution on the hub endwall of a model turbine vane passage. Heat transfer measurement without secondary air injection revealed a high heat transfer region which occurs over a small area around and upstream of the vane leading edge. Secondary air injection through slot upstream of the vane leading edge at a blowing ratio 1.3 greatly reduced the heat transfer in the regions near the vane leading edge and the vane pressure side within passage.

As one of the design parameter of endwall upstream slot, axial location of the slot plays an important role on film cooling performance of the vane endwall domain. Kost and Nicklas [9] and Nicklas [10] carried out both the thermodynamic and aerodynamic measurements in a linear turbine cascade with transonic flow field. Strong variations in heat transfer and film-cooling effectiveness due to the interaction of the coolant air and the secondary flow field were found. The result showed that the horseshoe vortex was strengthened by the ejection of coolant from the leakage gap at a mass flow ratio of 1.3%. This was attributed to the slot position, which is located at the place of the saddle point. Other study by Kost and Mullaert [11] investigated the effect of moving the slot to 0.3 Cax upstream of the vane leading edge. They found that moving the slot location properly can avoid intensifying the strength of the horseshoe vortex effectively. It could be proved that the saddle point of the upstream endwall boundary layer stagnation region is a sensitive region where the coolant ejection should be avoided. It was also found that slot at 0.2 Cax can provide better coverage even with less than half of the amount of coolant. Thrift et al. [12] also investigated the effects of slot axial position and orientation. Results indicated a significant increase in area-averaged effectiveness for the 45° relative to the 90° orientation. It was shown that moving the 90° slot close to the vane leading edge could improve local and area-averaged effectiveness. Unlike the two further upstream locations, the size of the induced vortex was greatly reduced while the vortices intensity increased.

Meanwhile, the effect of slot incline angle cannot be underestimated and should also be considered as a design parameter of endwall cooling flow. A systematical experiment has been reported for different injection schemes upstream of the vane leading edge with a contoured endwall by Burd et al. [13,14] and Oke et al. [15]. In these studies coolant was injected from a interrupted, flush slot that was inclined at 45° upstream of the vane. They also found that most of the coolant swept toward the suction side at the low slot flow rate. As they increased the percentage of the slot flow to 3.2% of the exit flow, the effectiveness of endwall cooling acts as an even better performance within the vane passage.

Apart from the variation of the slot parameter, Knost and Thole [16] presented computational results of the film cooling effectiveness of two endwall cooling hole patterns combined with a flush slot upstream of the vane. Comparison between predictions and experiments of a flush slot alone showed remarkable agreement. The resulting endwall effectiveness from slot cooling alone showed a pattern that was quite non-uniform along the endwall with most of the coolant being swept toward the suction side of the vane. One could expect a burn-out near the vane-endwall junction would be happened if only slot alone provides the coolant. Hada and Thole [17] conducted computational predictions of endwall adiabatic effectiveness with midspan gap and upstream slot. The results indicated that computational predictions agree relatively well with the measured adiabatic effectiveness on the endwall.

Other meaningful investigations are also enlightening. Take Colban's finding [18] as an example. He examined the effects of varying the combustor liner film-cooling and junction slot flows on the adiabatic wall temperatures measured on the platform of the first vane. Flow field and endwall effectiveness contours for a backward-facing slot with several different coolant exit conditions