International Journal of Heat and Mass Transfer 90 (2015) 1–14

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Film cooling effectiveness distribution of cylindrical hole injections at different locations on a vane endwall

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ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 9 June 2015
Accepted 9 June 2015

Keywords:
Film cooling
Endwall
Adiabatic film cooling effectiveness
Secondary flow

ABSTRACT

The secondary flow vortices make the flow field near the endwall highly three-dimensional. The jet-to-secondary flow interaction may help to make an efficient film cooling arrangement to cool the endwall. Six rows of cylindrical hole injection placed at different locations on a typical flat vane endwall with different density ratios and matched averaged blowing ratios to the engine condition were investigated experimentally in this work. Detailed measurements of adiabatic film cooling effectiveness distribution using PSP technique as well as the pressure distribution of the endwall were performed. The results showed that the endwall film cooling was mainly influenced by the passage vortex and endwall cross flow which prevented the cooling jet from covering the regions close to the leading edge and pressure side. The theoretical analysis indicated that the local blowing ratio of endwall film cooling increased as the local static pressure increased. The cooling jets with higher local blowing ratios were more sensitive to the change of the coolant supply pressure. Film injections located in high static pressure zones with a high momentum flux ratio had the potential to reduce the intensity of secondary flow and provided coolant to the near leading edge and pressure side regions.

1. Introduction

As the energy demand of the whole world rises, gas turbine has become an indispensable power-equipment in many fields because of its high efficiency and low emission. To further increase the output and efficiency of modern gas turbine, the turbine inlet temperature and single-stage load are increased which results in a higher thermal load and more three-dimensional aerodynamic loss [1]. In order to reduce NOx emissions and other pollutants generated during combustion, premixed combustor is preferred [2,3]. The employment of premixed combustor will change the combustor exit temperature profile from a parabola to a more uniform one [3]. Hot spot may occur from 10% to 90% vane span. These will directly affect the cooling of the first stage vane especially the endwall region.

The secondary flow structures make the flow field near the endwall highly three-dimensional. The vortices originate from the leading edge horseshoe vortex migrate and develop through the entire passage [4]. The early researches on endwall mainly focused on the flow field structures, aerodynamic and heat transfer characteristics when it was unnecessary to cool the endwall [5–7]. Afterwards discrete film holes were applied to the endwall cooling. Quite a few investigations found that the complex flow field in the near endwall region has a significant effect on the endwall film cooling and most of them showed negative effect of endwall secondary flow. Takeishi et al. [8] studied the influence of secondary flows in the passage on endwall film cooling and found that the endwall film cooling jets were deflected from the pressure side to the suction side. Thomas et al. [9] conducted experimental and numerical investigation of 1st stage vane endwall film cooling and found that due to the complex vortex and effect of pressure gradient, the areas close to leading edge and pressure side as well as the region around trailing edge were difficult to be cooled. Wright et al. [10] showed that the vortices formed upstream of the blade cascade would greatly reduce the endwall film cooling effectiveness. Based on a systematic study of endwall film cooling, Friedrichs et al. [11–13] proposed several distinct regions requiring individual cooling hole placements because of the influence of complex flow field near endwall and optimized the endwall film cooling depending on the flow pattern near the endwall. However the secondary flow is not always harmful to endwall cooling. Experimental results from Zhang et al. [14] and Zhang et al. [15] showed that the secondary flow and horseshoe vortex could carry the film cooling discharged from showerhead and pressure side to cover the endwall.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.06.026
0017-9310/

Nomenclature

C	gas concentration [–]
C_{ax}	axial chord length [m]
C_d	discharge coefficient [–]
D	hole diameter [m]
$D.R$	density ratio [–]
I	light intensity [cd]
I	momentum flux ratio [–]
k	constant [–]
L	hole length [m]
M	blowing ratio [–]
Ma	Mach number [–]
N_2	nitrogen [–]
O_2	oxygen [–]
P	pressure [Pa]
$P_{t,\infty}$	total pressure of the mainstream inlet [Pa]
$P_{s,m}$	static pressure of the mainstream [Pa]
$P_{t,c}$	total pressure of the coolant inlet [Pa]
p	pitch length [m]
R	gas constant for air [J/kg K]
Re	Reynolds number [–]
S	vane span [m]
T	temperature [K]
$T_{t,\infty}$	total temperature of the mainstream inlet [K]
$T_{t,c}$	total temperature of the coolant inlet [K]
U	velocity [m/s]
X, Y, Z	coordinates [m]

Greeks

α	inclined angle [°]
β	compound angle [°]
δ	boundary layer thickness [m]
η	film effectiveness [–]
ρ	density [kg m^{-3}]

Subscripts

aw	adiabatic wall
ax	axial
c	coolant
m, ∞	mainstream
r	recovery
ref	reference point
s	static
t	total/stagnation

Acronyms

CCD	charge-coupled device
CFD	computational fluid dynamics
LED	light emitting diode
MFR	mass flow ratio
PS	pressure side
PSP	pressure sensitive paint
PIV	particle image velocimetry
SS	suction side

Meanwhile, the film cooling jets also affect the flow field and development of vortex near the endwall. Many experimental and numerical works have investigated the influence of film injection on the endwall cooling in front of the leading edge [16–18]. Recently with aid of non-intrusive measurement techniques, more parameters are studied. Zhang and Jaiswal [19] measured the surface distribution of film cooling effectiveness by using PSP technique. The results indicated the existence of a strong interference between the cooling jets and the endwall secondary flows. PSP technique was also used by Wright et al. [20] to study the film cooling effectiveness distributions on a blade platform with both purge flow and discrete film holes. Takeishi et al. [21] investigated the influence of film cooling jet on leading edge horseshoe vortex employing LIF, PIV techniques. They concluded that enough amount of coolant or reasonable combination of distance and blowing ratio could efficiently reduce the vortex intensity. However, the horseshoe was enhanced if the inclined angle was too large or blowing ratio was not high enough. Thrift and Thole [22] studied the effect of trench flow injection angle upstream of leading edge on the endwall cooling. The results showed the influence of blowing ratio and injection angle on endwall heat transfer and the formation of horseshoe vortex.

A certain number of studies were carried out to investigate the performance of full coverage endwall film cooling as well as the reliability of numerical tools. Barigozzi et al. [23] studied the effects of a fan-shaped hole endwall cooling geometry on the performance of a nozzle vane cascade. The results indicated that the passage vortex and the 3D effects were weakened at high injection rates leading to a strong reduction of the endwall cross flow. Knost and Thole [24,25] conducted measurements of two endwall film cooling hole patterns combined with cooling from a flush slot that simulates leakage flow between the combustor and turbine sections. They found that the momentum flux ratio had a significant impact on cooling performance. Moreover their results showed that the adiabatic film cooling effectiveness levels and thermal spreading were not well predicted by CFD relative to the experimental data. Charbonnier et al. [26] investigated a film cooled platform experimentally and numerically. Although they found good agreement of experiment and computations local, differences still existed especially downstream of the passage. Andrei et al. [27] performed PSP measurement of film cooling effectiveness on a real engine vane. They found good adiabatic effectiveness downstream the location of throat because of the superposition of film cooling. However due to the secondary flow, the fillets were not well protected.

Although there have been many investigations on endwall film cooling published in literature, studies on single row film cooling characteristics in an endwall environment are rare. For a complex full coverage or multi-row film cooling endwall, the interactions between upstream and downstream injections as well as with the mainstream make the results more specific and geometry dependent. The complexity makes it not easy to explain some phenomenon without single row film cooling characteristics. Moreover, detailed measurements of single row film cooling characteristic on an endwall at different locations and conditions are necessary for the systematic validation of a numerical method and other empirical endwall film cooling prediction methods with correlations. Valid design and prediction tools are of vital importance for such a three dimensional complex region.

In this paper, six rows of cylindrical hole injection placed at different locations on a typical flat vane endwall with different density ratios and matched averaged blowing ratios to the engine condition were investigated experimentally. Detailed measurements of aerodynamic and adiabatic film cooling effectiveness distribution of the endwall were performed. The influence of averaged blowing ratio and density ratio as well as the interaction between the local secondary flow and film cooling jets were discussed.