International Journal of Heat and Mass Transfer 64 (2013) 401–417

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigations of the film cooling heat transfer coefficient of a Micro-Tangential-Jet scheme on a gas turbine vane

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ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 24 April 2013
Accepted 25 April 2013
Available online 20 May 2013

Keywords:
Gas turbines
Film cooling
Micro film cooling
Tangential injection
Heat transfer coefficient
Net heat flux reduction

ABSTRACT

This paper presents experimental investigations of the Heat Transfer Coefficient (HTC) performance of a Micro-Tangential-Jet (MTJ) Film cooling scheme on a gas turbine vane using transient Thermochromic Liquid Crystal (TLC) technique. The MTJ scheme is a micro-shaped scheme designed so that the secondary jet is supplied parallel to the vane surface. In order to supply the jet in a direction parallel to the vane surface, extra material was added on both pressure and suction sides. The film cooling performance of one row of holes on both pressure and suction sides were investigated at a blowing ratio ranging from 0.5 to 1.5 on the pressure side and 0.25 to 0.625 on the suction side, calculated based on the MTJ scheme exit area. The average density ratio during the investigations was 0.93, and the Reynolds number was 1.4E+5, based on the free stream velocity and the main duct hydraulic diameter. The pitch to diameter ratio of the cooling holes is 5 on the pressure side and 6.5 on the suction side. The turbulence intensity during all investigations was 8.5% and was measure two chords upstream the vane leading edge using the PIV technique. The investigations showed that the increase in the HTC ratio due to the presence of the MTJ scheme is very close to that resulting from the presence of normal traditional shaped schemes on the pressure side. Meanwhile, a reduction in the HTC ratio is recorded on the suction side. Such performance is attributed to the small overall height of the scheme which helped keep the resulting turbulence to a minimum. Moreover, the HTC distribution downstream the MTJ scheme is uniform in the lateral directions which helps minimize the thermal stresses. The Net Heat Flux Reduction (NHFR) parameter is used to judge the overall performance of the MTJ scheme. The NHFR represents a combination of the effects of both the cooling effectiveness and the HTC. Great enhancement in the NHFR performance of the MTJ was observed compared to traditional shaped schemes. With the current MTJ scheme design and dimensions and under the previously mentioned Reynolds number and turbulence intensity it was observed that a blowing ratio close to unity, calculated based on the scheme exit area, provides an optimal film cooling performance on both pressure and suction sides.

1. Introduction

In addition to designing efficient film cooling schemes from an effectiveness point of view, care must be given to the HTC performance as well. Numerous schemes have been proposed and good effectiveness performance was achieved but its net film cooling performance was negative because of the resulting increase in the HTC, compared to the cases when no film cooling was applied. Recently, researchers started paying attention to this point and the HTC performance became a basic parameter in judging the performance of any newly proposed film cooling scheme.

The vortical structure downstream the injection scheme has significant effect on the film cooling performance and as a result many research works have been conducted to propose solutions to control its strength. Ekkad et al. [1] investigated the effect of different tab locations, on the upstream edge, on the downstream edge, and symmetrically along the spanwise edges on the film cooling performance of circular schemes. Placing tabs along the upstream edge showed enhanced effectiveness performance but at the same time the HTC increased. The enhancement in the effectiveness was higher than the increase in the HTC and the net performance, represented in the NHFR, was positive. The other tab locations showed lower film protection than the case with no tabs. Nasir et al. [2] completed the study of Ekkad et al. [1] by investigating the effect of upstream tab orientation on the film cooling performance. They examined three different tab orientations, parallel to the surface, 45° upwards and 45° downwards. For both velocity and turbulence intensity profiles it was noticed that the defect

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.04.059

Nomenclature

Symbols

Br	blowing ratio ($\rho_j u_j/\rho_m u_m$)
C	cord length (m)
C_p	specific heat at constant pressure (kJ/kg K)
d	diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
Ma	Mach number
N	number of images captured per test
n	exponential constant
P	pressure (N/m^2)
p	film hole pitch (m)
q''	heat flux (W/m^2)
Re	Reynolds number ($\rho D_h U_m/\mu$)
s	height (m)
T	temperature (K)
t	time (s) and thickness (m)
u	velocity (m/s)
w	width (m)
x	streamwise distance on airfoil surface from hole exit
X	axial direction
α	thermal diffusivity (m^2/s), =($k/\rho C_p$)
η	film cooling effectiveness (($T_f - T_m$)/($T_j - T_m$))
ρ	density (kg/m^3)
φ	expansion angle (°)

Subscripts and superscripts

aw	adiabatic wall
c	centerline
f	film
h	hydraulic
i	initial
j	jet
m	main stream
o	stagnation and without
s	streamwise
w	wall

Abbreviations

CRVP	Counter Rotating Vortex Pair
DAQ	Data Acquisition
HTC	Heat Transfer Coefficient
MTJ	Micro-Tangential Jet
NHFR	Net Heat Flux Reduction
RGB	Red–Green–Blue
TIFF	Tagged Image File Format
TLC	Thermochromic Liquid Crystal

occurring in the boundary layer by the downward oriented tabs was maximum. The increase in the HTC was much less than the enhancement in the effectiveness when horizontal and downward oriented tabs were used and correspondingly, the net film cooling performance accompanying the use of horizontal or downward oriented tabs was positive. Upward oriented tabs showed very bad film cooling performance and because of that the researchers concluded that for the tabs to be effective they should interact with the flow exiting the film cooling hole rather than the cross flow. The tabs proposed by Ekkad et al. [1] and Nasser et al. [2] were not suitable from a practical point of view. In order for the tab geometry to be more applicable, Yang and Zhang [3] proposed placing ridge-shaped tabs along the upstream edge of the circular holes. The ridge shaped tabs resulted in good enhancement in the effectiveness, more than 100% over the baseline case in some regions, but the HTC increased over the base line case due to the increased turbulence. A reduction of about 100% in the heat flux without film cooling was recorded for the holes with the largest ridge-shaped tabs installed. The main disadvantage of such ridge-shaped tabs was the increased pressure drop across the cooling hole, compared to the base line case.

With a close idea to the use of discrete tabs, Li et al. [4] proposed the nozzle scheme. The nozzle scheme is a normal circular scheme with shaped orifices being placed at different locations and orientations inside it. They presented the film cooling effectiveness performance and the strength of the corresponding vortices of three different designs as well as the base line case. The aim of the nozzle scheme was to control the velocity gradient at the hole exit and hence the strength of the CRVP. They succeeded in decreasing the strength of the CRVP and great enhancement in the film cooling effectiveness was obtained. They concluded that careful shaping of the scheme exit is required. Many researchers were expecting that the aim of shaping the scheme exit is to reduce the secondary jet momentum, which is true, but shaping the scheme exit can also be used for reducing the strength of the vortical structure downstream the scheme exit, instead of increasing it, by carefully selecting the scheme lateral and span-wise expansion angles.

Na and Shih [5] investigated numerically the effect of different upstream backward ramp angles, 8.5°, 10° and 14°, on the film cooling performance of circular schemes. They stated that the presence of a backward upstream ramp results in an increase in the film cooling effectiveness that equals twice the one obtained without a ramp. They related this performance to the shift up of the boundary layer off the surface due to the presence of the ramp and hence to the minimization of the mixing between the jet and the main stream at the surface. The findings of Chen et al. [6] were not in agreement with those of Na and shih [5]. They stated that the presence of a backward ramp results in a negative effect on the film cooling performance at low blowing ratios, a reduced effectiveness, and increased HTC. The researchers related such performance to the generated vortices in the re-circulation region in the back of the ramp which works to increase the mixing between the two streams through increasing the turbulence intensity. For high blowing ratios, $Br > 1.0$, a slight enhancement was recorded, because the jet momentum was strong enough to penetrate out of the recirculation zone. The results of Chen et al. [6] seem more realistic than those of Na and Shih [5].

Harrison et al. [7] presented detailed film cooling performance of circular holes impeded in transverse trenches over an airfoil vane suction side experimentally. They applied both heated and non-heated upstream conditions to isolate the hydrodynamic effects of the trench and to highlight the effects of the thermal boundary layer. Also, they explored the effect of tripped and un-tripped boundary layer approaches. Trenched holes results from spraying the airfoils with Thermal Barrier Coating (TBC). They found significant effect of the starting length conditions on the HTC. They observed higher increase in the HTC augmentation when the starting length was heated in comparison to when the starting length was not heated. They related this to the displacement of the thermal boundary layer by the injected gases. Also, the condition of the boundary layer, tripped or un-tripped,