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Experimental investigations of the film cooling effectiveness of a micro-tangential-jet scheme on a gas turbine vane

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ABSTRACT

This paper presents experimental investigations of the film cooling effectiveness 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 tangentially to the vane surface. The scheme combines the benefits of micro jets and tangential injection. 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. 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%. Minor changes in the Mach number distribution around the airfoil surface were observed due to the presence of the MTJ scheme, compared with the case with no MTJ scheme. The investigations showed great film cooling performance for the MTJ scheme, high effectiveness values and excellent lateral jet spreading. The performance of tangential injection over actual airfoil surfaces was found close, qualitatively, to that observed over flat plate. A 2-D coolant film was observed in the results, which is a characteristic of the continuous slot schemes only. The presence of this 2-D film layer helps minimize the rate of mixing between the main and the secondary streams. This film help establish uniform thermal loads on the surface. Furthermore, it was noticed that the rate of effectiveness decay on the suction side was lower than that of the pressure side while the lateral jet spreading on the pressure side was better than on suction side. The main disadvantage of the MTJ scheme is the increased pressure drop across the scheme, compared to traditional shaped schemes.

1. Introduction

During the past few decades, numerous research works have been conducted in the area of gas turbine engines cooling to introduce better cooling techniques that can cope with the increasing demand of power generation. Combustion gases enter the turbine at very high temperatures reaching 1900 K, so efficient cooling techniques are essential to protect the engine components. Internal passage cooling, impingement cooling on the inner surfaces, and film cooling are the typical cooling techniques being used nowadays. Among all of these cooling techniques, film cooling is the most important one. Besides developing cooling techniques, a lot of research has been conducted in the area of material strength enhancement. 11 °C/year average increase in the maximum operating temperature of gas turbine engines were recorded due to thermal enhancements compared to only 5 °C/year due to components material properties enhancements, Downs and Landis [1]. It is clear that the inlet temperature increase due to thermal enhancement is more than twice that is due to the component material strength enhancement.

Most of the research efforts have been allocated to design cooling schemes with superior film cooling performance. Superior film cooling performance means high effectiveness, low heat transfer coefficient increase compared to the case with no film cooling, and optimal lateral coverage. The inclination angle of the injection scheme is of special importance because it highly affects the performance of the scheme. Zero inclination angle, otherwise known as tangential injection, was shown to be the best scenario by Goldstein et al. [2], Hartnett et al. [3], Wieghardt [4], and many others. Numerous experimental investigations had been conducted to investigate the effect of different geometrical and flow parameters on the film cooling performance of slot schemes with tangential injection. Kacker and Whitelaw [5] stated that the film cooling effectiveness increases as the lip thickness to slot height ratio decreases, and is the most effective parameter in the case of

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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 transfer 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
PIV	Particle Image Velocimetry
RGB	Red–Green–Blue
TIFF	Tagged Image File Format
TLC	Thermochromic Liquid Crystal

tangential injection. Ideal step slot, ideal submerged slot, thick lip ideal step slot and metered slot are previously proposed tangential injection slot designs. Burggraf and Huffmeier [6] compared the performance of the previously mentioned slot types and they concluded that the film effectiveness is adversely affected by metering geometries and the lip thickness, when compared to ideal slot performance. In order to sustain reasonable material strength, the continuous slots were replaced with discrete circular holes placed in parallel to the test surface. Nina and Whitelaw [7] investigated thirteen different configurations of discrete hole injection slots. To enhance the performance of discrete holes tangential injection schemes, Folayan and Whitelaw [8] proposed a combined tangential and normal injection slot scheme with finite lip thickness and they concluded the following; (1) the effectiveness increases with increasing the velocity ratio, lip length, and open area ratio, (2) for a given coolant flow rate, the influence of tangential to normal momentum ratio increase is small and tends to improve the effectiveness, and (3) a single row of tangential holes with small pitch to diameter ratio results in better performance than combined tangential and normal holes.

Shaped-discrete-hole schemes were proposed to sustain reasonable material strength and good film cooling performance at the same time. Numerous designs were proposed and investigated in literature. An Attempt to approach slot injection performance, Sargison et al. [9,10] proposed and experimentally investigated the film cooling performance of a converging-slot-hole (console) scheme over a flat plate and a gas turbine transonic vane. The scheme entry section is circular and then expands in the lateral direction and converges in the streamwise direction. For optimal lateral coverage they designed the scheme with no gabs between the holes exits. The console scheme showed good effectiveness performance on both flat plate and vane surface. Liu et al. [11,12] investigated the film cooling performance of the console scheme over a gas turbine blade, and the effect of different exit-entry area ratio on the film cooling performance of the console scheme over a flat plate, respectively. To improve the coolant lateral spreading of the console scheme, Liu et al. [13] proposed the waist-shaped console scheme. The waist pushes the coolant towards the sides of the scheme in order to help sustain a better coverage to the area between the holes.

Combining the jet impingement benefits with film cooling in one scheme, Zhang and Hassan [14,15] numerically investigated the film effectiveness of one row and two rows of the louver scheme over a flat plate. The louver scheme is a normal shaped hole with an internal 90° bend, circular hole followed by a squared cross sectional slot. Ghorab et al. [16], Elnady et al. [17] experimentally examined the performance of the louver scheme over a flat plate, and an actual gas turbine vane, respectively. The hybrid scheme is similar to the louver scheme and was proposed and experimentally investigated by Ghorab and Hassan [18]. Fan-shaped and laidback fan-shaped schemes were proposed and investigated numerous times in literature at a variety of flow and geometrical conditions on both flat plate and actual airfoil geometries by Thole et al. [19], Gritsch et al. [20,21], and many others. Lu et al. [22,23] investigated experimentally the film cooling performance of trenched and cratered film cooling holes. All previous investigations showed enhancement in the film cooling effectiveness performance of shaped schemes as compared to circular schemes in terms of effectiveness values and lateral jet spreading. Meanwhile, slight differences were recorded between these shaped schemes and each other.

Gau et al. [24] experimentally investigated the performance of micro-free-jet flow using a micro slot nozzle manufactured by Micro-Electro-Mechanical System (MEMS) technique. They examined three different slot heights, 50, 100 and 200 μm, at different Reynolds numbers using flow visualization and instantaneous velocity measurements. They observed the absence of the boundary vortices accompanying macro jets and, as a result, the micro jet exhibits the slowest rate of decay in the centerline velocity and the slowest rate of increase in the centerline turbulence intensity. This slow decay enables the micro jet to penetrate much deeper than the macro jet. Li et al. [25] experimentally investigated the film cooling performance of a micro slot over a flat plate. Different slot heights and different lip thicknesses were investigated at a blowing ratio ranging from 2.5 to 12.5. The authors concluded that the coolant amount supplied to the micro slot is two or three times order of