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Cooling effectiveness of shaped film holes for leading edge

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ABSTRACT

An experimental investigation has been carried out to improve the film cooling performance at the leading edge of a gas turbine vane. The standard cylindrical holes, located on the stagnation line, are modified with two expansion levels at the hole exit, 2d and 4d. A two-dimensional cascade has been employed to measure the cooling effectiveness of the two expansion levels and the standard hole using the transient Thermochromatic Liquid Crystal technique. The air is injected at 90° and 60° inclination angle relative to the vane surface with four blowing ratios ranging from 1 to 2 at a 0.9 density ratio. The Mach number and the Reynolds number of the main stream based on the cascade exit velocity and the axial chord are 0.23 and 1.4E5, respectively. The detailed local cooling effectiveness downstream the film holes over both the pressure side and the suction side are presented in addition to the lateral-averaged cooling effectiveness. The proposed expansion enhances the coolant distribution over the leading edge, particularly toward the suction side. The effectiveness increases toward the pressure side as well, yielding uniform thermal stresses around the stagnation line. The cooling effectiveness improved with increasing blowing ratio due to the jet lift-off reduction, hence higher cooling capacity is provided.

1. Introduction

With an elevated importance on environmental sustainability and the depletion of fossil fuel resources around the world, it has become increasingly necessary to improve the efficiency and hence increase the power/weight ratio for the next generation of gas turbines. The severe increase in the rotor inlet temperature demands an equivalent increase in the cooling capacity to protect the airfoil surface from this harsh thermal environment. Therefore, many studies have been conducted to increase the cooling capacity by improving the shape exit of the film holes (e.g. Gritsch et al. [1–3], Cho et al. [4], and Yu et al. [5]. Bunker [6] reviewed the development of the shaped hole, its impact on the film cooling performance, and presented many studies that contributed to this development. Enhancing the film cooling performance on the leading edge requires further investigation because of the high curvature of the airfoil surface at this region in addition to the sever increase in the temperature, particularly on the first stator. Several experimental investigations has been conducted to measure the film cooling performance on the leading edge either over simulated cylindrical surfaces or over airfoil in a cascade. Moreover, several numerical studies were performed to reveal the physics beyond the highly complex flow at that region.

Simulating the leading edge as a half cylinder, Mehendale and Han [7] experimentally studied the effect of turbulence intensity on the film cooling performance of standard cylindrical holes at different blowing ratios. As the mainstream turbulence increased, the effectiveness decreased as the dilution of coolant in the main flow increased. The heat transfer coefficient and effectiveness were found to decrease with increasing hole spacing, because of less flow interaction and less coverage. The moderate blowing ratios gave the best lateral cooling performance as it was neither weak enough to be diluted in the mainstream nor strong enough to deeply penetrate through the mainstream. Using the same model, Ou and Han [8] concluded with the same findings for slot holes.

Using a half cylindrical model, Salcudean et al. [9] experimentally investigated the effect of coolant density on the film cooling effectiveness through single and double row injection. The effectiveness of air as a coolant is better than that of the CO_2 near downstream of the injection site for all blowing ratios. The moderate blowing ratios showed a peak effectiveness that changed with the variation of hole position with respect to the stagnation line. They found that the position of the holes in the stream wise direction had an influence on the effectiveness as each position had its own pressure gradient, local velocity, boundary layer thickness, and local static pressure acting on the hole. Due to the difference in local static pressure for each row of holes, the coolant flow rate of the front row severely decreased at lower blowing ratios, especially at higher density ratios. The effectiveness of both coolants decreased farther downstream, with better performance for CO_2

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Nomenclature

C	true chord (cm)
C_p	specific heat capacity (J/(kg K))
C_x	axial chord (cm)
d	hole diameter (mm)
h	heat transfer coefficient with film cooling (W/(m^2 K))
h_o	heat transfer coefficient without film cooling (W/(m^2 K))
I	momentum ratio.
k	thermal conductivity (W/m K)
L	chord length (mm)
p	pitch (distance between two holes) (mm)
q	heat load (W)
s	linear distance downstream the cooling hole (mm)
T	temperature (K)
T_i	initial temperature of the surface (K)
t	time (sec)
v	velocity (m/s)
z	direction spanwise the cooling hole

Greeks symbols

α	thermal diffusivity (m^2/s)
γ	specific heat ratio, $\gamma = C_p/C_v$
η	film cooling effectiveness
λ	inclination angle (°)
ρ	density, (kg/m^3)

Subscripts

c	coolant
elec	electric
f	film
j	jet
loss	losses
m	main flow
w	wall (surface)

Acronyms

Br	blowing ratio $[(\rho v)_j/(\rho v)_m]$
DR	density ratio (ρ_j/ρ_m)
HTC	heat transfer coefficient
PR	pressure ratio (P_j/P_m)
PIV	particle image velocimetry
ROI	region of interest
TLC	thermochromic liquid crystal

injection at higher blowing ratios as the denser coolant had lower velocity. An arrangement of two rows in line improved the effectiveness for moderate and higher blowing ratios compared to a staggered arrangement. Using the TLC transient technique with the same base geometry as Mehendale and Han [7] and Ekkad et al. [10] investigated the cooling performance of injection near downstream the stagnation line at two different density ratios. The high density injection showed peak effectiveness at moderate blowing ratio, however the effectiveness with the low density injection continued to increase up to higher blowing ratio. The same findings as Salcudean et al. [9] and He et al. [13].

Investigating the effect of showerhead intensity, Hoffs et al. [12] measured the cooling performance with three-row and four-row configurations over a cylindrical model using the TLC technique. They reported a decrease in the cooling effectiveness with blowing ratio and they found a strong decrease in the effectiveness with varying mainstream incident angle at low blowing ratios. The four row configuration provided higher cooling effectiveness and was not influenced by varying blowing ratio. Using the transient TLC technique, Reiss and Bolcs [14] measured the cooling performance of three cooling hole shapes on the showerhead region at two Mach numbers. They reported a decrease in the effectiveness with increasing Mach number due to the thinner boundary layer associated with high mainstream velocity. The jet had more of a tendency to penetrate through the thinner boundary layer with different penetration degrees for each exit shape. With a more expanded exit, the strength of the jet to penetrate decreased and the effect of Mach number became insignificant.

All the aforementioned studies were performed for a cylinder model in a cross flow. This model simulates the leading edge region with certain approximation downstream the hole because of the curvature difference between the cylindrical model and the leading edge profile. Modeling the leading edge as an elliptic surface, [15,16] numerically investigated the cooling performance of a standard cylindrical hole and diffused shaped hole at the stagnation line. They found that the higher blowing ratios, limited by Br = 2, provided higher effectiveness and better lateral coverage when injected from the stagnation line in the case of a cylindrical hole. Contrarily, the higher blowing ratios had lower effectiveness if injected from the downstream rows, because of the lower local static pressure that allowed the jet lift-off. They also reported an increase in the effectiveness with the diffused exit, however it was accompanied by an increase in the flow ingestion downstream of the hole exit.

Using the PSP technique with a linear cascade, Zhang and Moon [17] measured the cooling performance of the showerhead arranged in different geometrical aspects with the same coolant amount. They found that reducing the injection compound angle or increasing the hole diameter improved the cooling effectiveness. Investigating the hole exit shape, Weigand et al. [18] experimentally studied the cooling performance of different showerhead cooling geometries (cylindrical, fan-shaped, and conical) on a blunt body using the TLC technique. The conical shape showed the best effectiveness over a wide range of blowing ratios while the fan-shaped gave the best lateral coverage with the highest heat transfer coefficient, especially at higher blowing ratios. The cylindrical shape gave the lowest lateral coverage at higher blowing ratios.

Lu et al. [19] studied the effect of the hole angle and shaping on the cooling performance of turbine blade showerhead using a blunt body model. They found that the peak effectiveness just downstream of the hole decreased with an increase in the traverse angle of the cooling hole, with better performance far downstream. At low blowing ratios however, the effectiveness increased with increasing traverse angle. The effect of the blowing ratio variation was small compared to the effect of the injection angle itself. The shaping of the hole helped reduce the jet lift-off and decreased the lateral momentum, yielding an improved effectiveness.

Using the PSP technique and a similar model, Gao and Han [20] also studied the effect of the hole angle and shaping on the cooling performance of seven-row and three-row showerhead cooling. In the stagnation regions for all geometries, the mainstream momentum was small, so the coolant was injected in the radial direction without deflection, providing the poorest effectiveness. For the next rows, the mainstream momentum increased causing a noticeable deflection in the cooling jet along the streamwise direction, improving the coverage and effectiveness. This deflection decreased with increasing blowing ratio yielding a reduction in the effectiveness. The effectiveness of the compound angle was less