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Film cooling effectiveness distribution on first-stage vane endwall with and without leading-edge fillets

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ABSTRACT

Considered are the effects of leading edge airfoil geometry on endwall film cooling. Three different fillet profiles, with length to height ratios of 2.8, 1.2 and 0.5, are considered, as each is placed at the junction of the airfoil leading edge and endwall. The results of these arrangements are compared with a baseline configuration with no fillet. The film cooling is produced by four rows of compound-angle, laidback fan-shaped holes, where each row of holes is located in the lateral direction. Each fanshaped hole is inclined at an angle of 30° with respect to the endwall surface. The compound angles of the first, second, third, and fourth rows of holes are 0°, 30°, 45°, and 60°, respectively, relative to the axial direction. Each fanshaped hole has a lateral diffusion angle of 10° from the hole-centerline, and a forward expansion angle of 10° relative to the endwall surface. The Reynolds number based on the axial chord and inlet velocity of the free-stream flow is 3.5×10^5, and the testing is done in a four-blade cascade with low Mach number condition (0.1 at the inlet), while the overall-average blowing ratio of the coolant through the discrete holes is constant at 0.4. Local, surface adiabatic film-cooling effectiveness values are measured using pressure sensitive paint (PSP). For a blowing ratio of 0.4, the baseline geometry (with no fillet) provides the best film cooling performance near leading edge pressure side. As for the leading edge suction side, the best leading edge configuration is the longfillet arrangement, since it is more effective in controlling the suction side leg of the horseshoe vortex compared to the other configurations which are examined.

1. Introduction

The efficiency of a gas turbine increases with the increase of the turbine inlet temperature. Modern gas turbines are designed to operate at relatively high turbine inlet temperatures, which are above 1600 °C for some engines, which results in high thermal loads and increased thermal stresses on turbine components. In order to maintain the operating lifetimes of components when such challenges are present, adequate cooling of individual components is a necessity. The present investigation considers film cooling technologies as applied to the endwall region of a turbine blade passage, because of the extra challenges which are provided by the complex secondary flow structure and strong pressure gradients which are present. The presence of such phenomena makes the endwall considerably more difficult to cool than blade aerofoil surfaces.

Bogard and Thole [1], and Simon and Piggush [2] summarize recent literature on turbine passage aerodynamics and hear transfer. According to these and other investigators, the secondary flow structure within the nozzle guide vane passage is typically comprised of multiple phenomena. First, a horseshoe vortex develops near the airfoil leading edge, near the corner junction of the leading edge and the endwall. This horseshoe vortex is divided into the pressure-side leg and the suction-side leg. The transverse pressure gradient causes the pressure-side leg to advect across the vane passage, whereas the suction-side leg of the horseshoe vortex advects in a direction which is approximately parallel to the airfoil profile. The pressure side leg then becomes a passage vortex. Before this passage vortex impinges on the downstream half of the suction side of the adjacent vane, the passage vortex grows in size in the passage, entraining and mixing with low momentum fluid along and near the endwall, and resulting in locally augmented surface heat transfer rates. Then the downstream portions of the passage vortex and the suction-side leg of the horseshoe vortex then mix and intermingle with each other. Each one of these vortices then lifts off the endwall, and continues to advect adjacent to the vane suction side [1,2].

Recent investigations of endwall heat transfer with film cooling are described by a number of investigators. Friedrichs et al. [3] consider novel film cooling hole configurations to improve magnitudes of film cooling effectiveness on an endwall arrangement. Wright et al. [4] describe an experimental study to investigate the film

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Nomenclature

C	concentration
C_{ax}	axial chord length of blade profile
D	film hole diameter
i	cascade inlet incidence angle
I	light intensity
LE	leading edge
M	blowing ratio, $\rho cVc/\rho\infty V\infty$
P	static pressure
PS	pressure side
P_{O2}	partial pressure of oxygen
S	span of two-dimensional blade
$SPAN$	span of passage between pressure side and suction side at a particular X/C_{ax} location
SS	suction side
T	temperature
V	fluid velocity
X	axial coordinate
Z	lateral coordinate
Zp	passage span at inlet in lateral direction

Greek symbols

ρ	fluid density
η	local surface adiabatic effectiveness
$\overline{\eta}$	laterally-averaged surface adiabatic effectiveness
Θ	non-dimensional local fluid temperature, $(T - T\infty)/(Tc - T\infty)$

Subscripts

air	pure air condition
aw	adiabatic condition
c	coolant condition
G	global coordinate
mix	mixture condition
ref	reference value
∞	freestream condition

cooling effectiveness, as measured using three different steady state techniques: pressure sensitive paint, temperature sensitive paint, and infrared thermography. According to these investigators, all three approaches provide detailed distributions on surfaces near film cooling holes, with the best measurements beneath jet separation and reattachment regions captured with pressure sensitive paint. Zhang and Jaiswal [5] and Wright et al. [6] investigate film cooling effectiveness distributions on a turbine vane endwall surface using pressure sensitive paint. Effects of secondary flows through the vane passage are readily apparent in the measured distributions of surface film cooling effectiveness. Wright et al. [7] also employ pressure sensitive paint to examine the effects of wakes and vortices on platform film cooling. Upstream wakes have only negligible effects on platform film cooling effectiveness distributions, whereas significant reductions of film cooling effectiveness are present due to passing vortices. The effects of rotation on platform film cooling are investigated by Suryanarayanan et al. [8,9] who show that secondary flows near the endwall are strongly affected by rotational motion which enhances advection of coolant trajectories from the blade pressure surface to the blade suction surface.

Most papers which consider leading edge modifications address aerodynamic losses and heat transfer. For example, Praisner and Smith [10,11] investigate the unsteady and time-averaged leading edge horseshoe vortex, as well as secondary, tertiary, and corner vortices. According to these investigators, the horseshoe vortex is characterized by significant quasi-periodic unsteadiness. Bloxham et al. [12] and Kubendran et al. [13] employ a leading edge fillet and passive flow control to reduce the detrimental influences of the horseshoe vortex. Sabatino and Smith [14] consider boundary layer influences on unsteady horseshoe vortex flow and surface heat transfer. These authors indicate that other data presented in the archival literature support the hypothesis that the temporal behavior of the horseshoe vortex system is driven by the temporal characteristics of the impinging turbulent boundary layer. Hada et al. [15] consider the effects of inlet velocity, boundary layer thickness, and leading edge airfoil diameter on the horseshoe vortex and endwall heat transfer, using a low speed wind tunnel facility. Aunapu et al. [16] use endwall jets located in the center of a turbine passage to alter the path of the pressure side leg of the horseshoe vortex. Shih and Lin [17] study the effects of inlet swirl and leading edge fillet arrangements on aerodynamic loss and surface heat transfer as a result of the different vortex structures which form and develop within an endwall passage. Mahmood et al. [18] explore different fillet profiles, as they are employed to reduce the secondary flow structures and Nusselt numbers on and near an endwall. Instantaneous flow visualization images are utilized to compare the smaller horseshoe vortex structures near the stagnation region when leading-edge fillets are employed, compared to the horseshoe vortex structure for the baseline case when no fillet device is employed.

Using computational and experimental approaches, Zess and Thole [19] consider methods to alter the horseshoe vortex that forms at the leading edge of a gas turbine stator vane, and show, with the appropriate approach, that the leading edge horseshoe vortex can be eliminated. Becz et al. [20] present experimental results in the form of area-averaged total pressure loss coefficients for four different turbine airfoil leading edge configurations, and show how certain leading edge modifications significantly reduce losses in a high turning airfoil cascade. Lethander et al. [21,22] use computational fluid dynamics (CFD) predictions to design optimized fillet configurations with significant reductions in adiabatic wall temperature distributions. Han and Goldstein [23,24] utilize the heat/mass transfer analogy on a simulated turbine endwall with blade fillets, and show higher mass transfer regions with fillets near the leading edge on pressure and suction turbine airfoil surfaces. With the leading edge modified airfoil, corner vortices are intensified. Mahmood and Acharya [25] experimentally investigate the secondary flow structure in a blade passage with and without leading edge fillets. According to these investigators, in the early stages of secondary flow development, fillets are effective in reducing the size and strength of the suction side leg of the horseshoe vortex, with associated reductions in the pressure loss coefficients and pitch angles. Sauer et al. [26] use a leading edge bulb in the endwall region to intensify the suction side branch of the horseshoe vortex. With experiments, Pieringer and Sanz [27] study the influence of the fillet between blade and casing on the aerodynamic performance of a transonic turbine vane. The results show that the starting point of flow separation (at the corner between the suction side of blade and casing) is moved towards the trailing edge, as fillet radius increases.

The present paper compares film cooling effectiveness distributions over the endwall of turbine nozzle guide vane cascade, with three different leading edge fillet configurations, as well as for a