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An influence of novel upstream steps on film cooling performance

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ABSTRACT

In this study, computational simulations were made using ANSYS CFX to predict the improvements in film cooling performance by using novel upstream steps. These steps are curved shapes instead of the normal shapes. The film cooling effectiveness (η), the heat transfer coefficient (h) and the net heat flux reduction (NHFR) over flat plate were investigated and compared with experiments. The width of the curved steps was changed from (W) to ($W/8$). Blowing ratios in the range (0.5, 1, 1.5 and 2) were investigated.

Results show that the curved step with less width ($W/8$) gives higher laterally film cooling effectiveness, lower heat transfer coefficient and higher NHFR comparing with normal step, rectangular and circular film holes without step at all blowing ratios. Interpretation of the low and high heat transfer coefficient regions for curved step ($W/8$) depending on the flow structures was explained in detail.

1. Introduction

Modern gas turbines are designed to run at high turbine inlet temperatures well in excess of current metal temperature limits to improve thermal efficiency and power output [1]. In addition to improved temperature capability materials and TBCs, highly sophisticated cooling techniques such as augmented internal cooling and external film cooling must be used to maintain acceptable life and operational requirements under such extreme heat load conditions. Film cooling is the introduction of a secondary fluid (coolant or injected fluid) at one or more discrete locations along a surface exposed to a high temperature environment to protect that surface not only in the immediate region of injection but also in the downstream region and this technique will used in this paper.

Several researches and development activities are proved that using cylindrical holes in film cooling had disadvantages in gas turbine applications due to the jet lift off the surface, particularly at higher momentum flux ratios (~1 and above) leading to deterioration the film cooling performance. Therefore, the research for new developments to optimize film cooling performance has been intensified in recent years [2].

The film cooling performance parameters such as heat transfer coefficient (h) and film cooling effectiveness (η) to find the net heat flux reduction over blade surface are dependent on the film cooling geometry and the coolant and mainstream flow fields. Some studies have focused only on the heat transfer coefficient enhancement, and others have presented only film effectiveness results and others presented each of these parameters. In this paper each of the heat transfer enhancement and the film cooling effectiveness will be studied.

1.1. A review of studies on film cooling effectiveness

A large number of papers have been published on the topic of shaping the film cooling hole. Shaped holes have proven to provide the highest adiabatic effectiveness among film cooling configurations as investigated in Goldstein et al. [3], Sen et al. [4], Thole et al. [5] , Laveau and Abhari [6] and Gao and Han [7]. But the Shaped holes are expensive to manufacture. Instead of using holes with shaped exits, Na and Shih [8] have introduced a design concept where an upstream ramp with backward-facing step is positioned directly in front of the cooling exit. Barigozzi et al. [9,10] have shown that an upstream ramp in the front of a cylindrical hole can have a thermal protection improvement. Rallabandi et al. [11] focused on the problem of determining the heat load reduction due to film-cooling holes with an upstream step. Abdala et al. [2] studied effects of twenty-one cases with different upstream steps on film cooling effectiveness and flow structures. They concluded that the steps with curvature given higher film cooling effectiveness than the other steps. But step studies need to determine the heat transfer coefficients in details and to optimize the steps dimensions.

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Nomenclature

B	pitch (space between the injection holes) (m)
D_h	hydraulic hole diameter (m)
DR	density ratio of coolant to mainstream, ρ_c/ρ_∞ (–)
h	heat transfer coefficient [W/m^2 K]
L	hole length (m)
M	blowing ratio of coolant to mainstream (–) $M = \text{DR} \times U_c/U_\infty$
NHFR	net heat flux reduction, $NHFR = 1 - \frac{h}{h_o}(1 - \eta * \phi)$
$\dot{q}$	heat flux rate (W/m^2)
S	step height (m)
T	temperature (K)
Tu	mainstream turbulence intensity (%)
U	velocity (m/s)
X	streamwise coordinate along model surface (m)
Y	vertical coordinate (m)
Yplus	non-dimensional wall distance

Greek symbols

ϕ	non-dimensional metal temperature, $(T_\infty - T_c)/(T_\infty - T_w)$
α	coolant injection angle (deg.)
η	adiabatic effectiveness, $(T_\infty - T_{aw})/(T_\infty - T_c)$
θ	non-dimensional temperature ratio, $(T_\infty - T)/(T_\infty - T_c)$
ρ	density (kg/m^3)

Subscripts

∞	mainstream
aw	adiabatic wall
c	coolant
o	without film cooling
w	wall temperature

Sister holes another technology investigated by Ely and Jubran [12] to increase cooling effectiveness by reducing pockets of reversed flow.

Nasir et al. [13] investigated triangular tabs are located along upstream edge of the holes. This tabs increased cooling effectiveness, but this application shown increase in pressure drop. Certain configurations of cylindrical holes embedded in transverse trenches have been shown to perform similarly to shaped holes, and trenches would be cheaper to manufacture than shaped holes. Several studies have investigated various trench configurations such as Bunker [14], Waye and Bogard [15], Lu et al. [16], Harrison and Bogard [17], Jia et al. [18], Zuniga and Kapat [19].

1.2. A review of studies on heat transfer coefficient

Heat transfer coefficients downstream of film injection are enhanced due to increased turbulence produced by mixing of the coolant jets with the mainstream boundary layer. This increased turbulence locally enhances the heat transfer coefficients [1]. Goldstein et al. [20] used a naphthalene sublimation to study the film cooling performance through a one row of film holes. They showed the regions of high and low mass/heat transfer around injection holes. Ammari et al. [21] presented a summary of results for film cooling on a flat surface with a single row of holes inclined at 35° along the mainstream direction. They showed that the heat transfer coefficient ratio decreases with increasing axial distance from the injection hole. About 15-hole diameter downstream of injection, the film cooling effect disappears. The heat transfer coefficient ratio is almost equal to unity. Hay et al. [22] presented the variation of the heat transfer coefficient ratio with the blowing ratio. They showed the effect of the blowing ratio is to increase the heat transfer coefficient ratio. The ratio is closer to unity at lower blowing ratios but increases to significantly high values at high blowing ratios. Ammari et al. [21] also presented the effect of density ratio on heat transfer coefficient ratio for two different coolant-to-mainstream density ratios of 1 and 1.52. It was observed that lower density injectant provides higher heat transfer coefficient at the same blowing ratio due to higher momentum. Sen et al. [4] and Ekkad et al. [23] studied the effect of compound angle holes on heat transfer coefficients. They showed that compound angle injection provides higher heat transfer coefficients than simple angle holes. This may be due to increased lateral mixing of jets with the mainstream producing increased local turbulence and thus enhancing heat transfer coefficients. This effect increases with higher blowing ratios. Gritsch et al. [24] presented heat transfer coefficient measurements for cylinder hole with fan shaped hole and laidback fan shaped hole configurations. The heat transfer coefficient ratios are highest for the cylinder hole. With increasing in blowing ratios, the heat transfer coefficient ratio increases. Heat transfer coefficients for the fan shaped holes are much lower due to increased cross-sectional area at hole exits. This decreases the momentum of the jet and reduces penetration into the mainstream. Rhee et al. [25] conducted an experimental study to measure the local film-cooling effectiveness and the heat transfer coefficient for four different cooling hole shapes such as a straight rectangular hole, a rectangular hole with laterally expanded exit, a circular hole and a two-dimensional slot are tested. The results showed that the rectangular holes provide better performance than the cylindrical holes. For the rectangular holes with laterally expanded exit, the penetration of jet is reduced significantly, and the higher and more uniform cooling performance is obtained even at relatively high blowing rates. The reason is that the rectangular hole with expanded exit reduces momentum of coolant and promotes the lateral spreading like a two-dimensional slot.

The above review revealed that the development of film cooling has aimed at producing high film effectiveness and low heat transfer coefficient, with uniform protection of the surface, using the minimum amount of coolant air to minimize the penalty of using film cooling. However, there is limited film cooling performance data of upstream steps to investigate film cooling effectiveness and heat transfer coefficients in depth, in literature.

In this paper, novel upstream steps will be used with a rectangular film hole to improve the film cooling performance.

The film cooling effectiveness and flow structures will be discussed. The heat transfer coefficient and net heat flux ratio over flat plate surface will be investigated. The influence of the blowing ratios on film cooling performance will be investigated.

2. Computation setup

In this study five cases with different upstream steps were studied as shown in Fig. 1. These cases consist of a normal step and curved steps with different widths. In all cases the film hole is rectangular cross-section with a hydraulic diameter of 10 mm for dimensions of $1.5D \times 0.75D$. The coordinate origin $X/D = 0$ was defined as the center of the hole. Dimensions of steps and computational domain are illustrated in Figs. 2 and 3.