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Investigation on film cooling performance from a row of round-to-slot holes on flat plate

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A B S T R A C T

A series of numerical computations are conducted to investigate the film cooling from a row of round-to-slot holes on a flat surface. Particular attention is paid to explore effect of slot width ($0.2 \leq s/d \leq 0.5$) on the film cooling performances of round-to-slot holes with a fixed slot length of $l/d = 2.0$ under typical blowing ratios ranged from 1.0 to 2.0. Besides, several experimental tests are also performed to obtain the film cooling effectiveness and discharge coefficient of the round-to-slot holes with specific geometries. The results show that the coolant flow turning towards both lateral sides due to the transitional flow passage of film-hole is dominated inside the round-to-slot hole. Owing to the specific interaction mechanism between the coolant jet issued from round-to-slot holes and the primary flow, the hot primary flow is mainly entrained into the coolant layer from the film-hole centerline. In general, the diffusing round-to-slot hole shows its favorable feature on the film cooling enhancement near the film hole. However, beyond a certain distance, the converging round-to-slot hole achieves a little higher laterally-averaged film cooling effectiveness than the diffusing round-to-slot hole. The converging round-to-slot hole with $s/d = 0.2$ produces higher laterally-averaged heat transfer coefficient than the cylindrical hole. While the diffusing round-to-slot hole produces less laterally-averaged convective heat transfer coefficient than the cylindrical hole beyond $x/d = 10$. The discharge coefficient decreases significantly as the slot width reduces.

1. Introduction

Film cooling technology has been extensively employed in the modern gas turbine engines for protecting the hot gas path components (such as combustor liners, turbine blades, exhaust nozzles, etc.) from overheating. The practical utilization of film cooling is commonly associated with the injection of cooling air through the discrete holes. As regard as the film cooling of the conventional or cylindrical discrete holes, two major problems are illustrated by previous works to be detrimental to the film cooling performance. Firstly, the coolant jets are usually easier to lift-off the protected surface, resulting in low film cooling effectiveness at higher blowing ratios. Secondly, the coolant jets are not capable of covering the zone between adjacent film holes, resulting in very non-uniform distribution of film cooling effectiveness in the lateral or spanwise direction. As for these reasons, considerable efforts have been devoted to the film cooling enhancement in past decades. A major advancement in the film cooling technology has been realized by the incorporation of exit shaping to the film holes [1].

Fan-shaped hole is one of the most common shaped holes, which has been extensively studied. Goldstein et al. [2] carried out an experiment on the film cooling effectiveness to demonstrate the film cooling effect of 35°-inclined axial shaped holes with lateral diffusion of 10°. A significant increase in the film-cooling effectiveness immediately downstream of the shaped holes as well as lateral coolant coverage was illustrated. Haven et al. [3] made an investigation on the shaped-hole cooling performance. It was found that there was an anti-kidney vortices effect in shaped film holes,

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Nomenclature

A	Area (m^2)
C_d	discharge coefficient
d	film hole diameter (m)
E_g	heat transfer coefficient ratio
h	convective heat transfer coefficient ($W/m^2 \cdot K$)
I	momentum flux ratio
L	hole length (m)
l	slot length (m)
M	blowing ratio
m	mass flow rate (kg/s)
P	holt-to-hole pitch (m)
p	pressure (Pa)
q	heat flux (W/m^2)
s	slot width (m)
T	temperature (K)
t	perforated wall thickness or film hole height (m)
u	velocity (m/s)
x	streamwise-direction
y	normal-direction
z	lateral-direction

Greek letters

ρ	density (kg/m^3)
θ	inclination angle of film hole (°)
η	film cooling effectiveness
ψ	pressure drop ratio
Θ	dimensionless temperature
Ω	dimensionless vorticity

Subscripts

ad	thermally adiabatic
aw	adiabatic wall
base	baseline or cylindrical hole
c	coolant or secondary flow
f	film
inlet	inlet of film hole
jet	coolant jet at film hole exit
out	primary flow outlet
w	wall
0	without film cooling
∞	primary flow

Superscripts

*	total

thus suppressing the strength and size of the kidney vortices. Gritsch et al. [4–6] presented measurements on adiabatic film cooling effectiveness, heat transfer and discharge coefficient for different fan shaped holes. Thole et al. [7] presented a detailed flow field measurement on fan shaped holes. It was illustrated that the fan-shaped hole lead to less shear mixing of the coolant jet with the primary flow, less penetration of the coolant jet into the primary flow, and wider lateral-coverage of the coolant jet related to the conventional hole. Kohli and Bogard [8] made an experiment to study the effect of hole shape on film cooling with large angle injection. It was reported that the hole with larger forward diffusion angle is expected to keep the coolant jet closer to the surface. However, film cooling effectiveness was lower than that of the hole with smaller forward diffusion angle. Bell et al. [9] and Yu et al. [10] investigated the film cooling performance of compound and diffusing shaped holes. It was illustrated that compound angle-shaped holes generally improves lateral coverage of coolant jet and produces higher effectiveness than the axially oriented holes. Recently, Lee and Kim [11] made a study on shape optimization of a fan-shaped hole to enhance film-cooling effectiveness using three-dimensional Reynolds-averaged Navier-Stokes analysis and surrogate approximation methods. Some geometric factors (such as injection angle, lateral expansion angle, length-to-diameter ratio, etc.) on the film cooling performance were taking into account. Colban et al. [12] developed a semi-empirical film cooling correlation to predict film cooling effectiveness of laidback fan-shaped holes on a flat-plate surface. It was indicated that the film cooling effectiveness is strongly affected by hole-to-hole pitch, blowing ratio, area ratio and width of hole at trailing edge of hole breakout.

It is notable that some innovative shaped-holes are proposed recently, including converging slot-hole (Console) [13,14], tabbed-shaped [15,16], arrowhead-shaped [17], dumbbell-shaped and bean-shaped [18], combined-hole [19,20], NEKOMIMI [21], etc. Among these shaped-holes, the converging slot-hole is of specific features, which is designed to offer the advantages of slot jet flow, while maintaining a structural strength similar to discrete holes. In this geometry, the coolant flow passage inside hole is turned gradually from an initially round cross section at the inlet to a finally rectangular slot at the exit with convergence in the axial direction and divergence laterally. Early investigations by Sergison et al. [13,14] demonstrated clearly the advantages of converging slot-hole on film cooling performance either in the flat plate tests or transonic cascade tests. Detailed flow field for the film cooling of converging slot-hole were investigated experimentally by Sergison et al. [22] and numerically by Azzi and Jubran [23] as well as Yao and Zhang [24]. It was interesting to find that the interaction between the coolant jet from inclined converging slot-hole and the primary flow results in a pair of counter rotating vortices originates from the edge of slot with a sense of rotation opposite to the kidney pair of conventional hole, which makes the coolant jet from the converging slot-hole be of the flow mechanism for suppressing normal penetration. Liu et al. [25] investigated the influence of geometric parameters of converging slot-hole, including divergence angle and exit-entry area ratio, on the film cooling performance. The investigations showed that properly changing the geometry parameters of converging slot-hole could improve the film cooling performance. Recently, Yao et al. [26,27] made a scaled model experiment and a numerical research to investigate the film cooling performance of a single row of converging slot-holes on the blade suction side. The results showed that the converging slot-hole is of great potential in the blade film cooling application to produce high cooling effectiveness, especially at large blowing ratios. However, this is at the expense of greater pressure drop of coolant jet across the film hole under the same blowing ratio or practical coolant mass-flow rate due to the gradual contraction of cross-sectional area of the converging slot-hole.

To our knowledge, relatively little efforts were devoted to reveal the effects of geometric factor of converging slot-hole on the film cooling performance. In addition, when the slot area at the film-hole exit is lager than that of round cross section at the inlet, the film hole will be a diffusing slot-hole. These two kinds of shaped holes may all be regarded as round-to-slot holes, either in