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Experimental and numerical study on the effects of rib orientation angle on film cooling performance of compound angle holes

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A B S T R A C T

To investigate the effects of the inclined ribs on internal flow structure in film hole and the film cooling performance on outer surface, experimental and numerical studies are conducted on the effects of rib orientation angle on film cooling of compound angle holes. Three coolant channel cases, including two ribbed cross-flow channels (135° and 45° inclined ribs) and the plenum case, are studied for three blowing ratios. The 2D contours of film cooling effectiveness and heat transfer coefficient are measured by transient liquid crystal measurement technique. The steady RANS simulations with realizable k-ε turbulence model and enhanced wall treatment are performed. The results show that the lateral spread of the coolant jet on the surface is paramount influenced by the rib orientation angle. The lateral spread of the 45° rib case is obviously larger than that of the 135° rib case for lower blowing ratios. For the blowing ratio of 1.0, the area-averaged cooling effectiveness for the 135 and 45° rib angles is higher by a factor of 38% and 107%, respectively, compared to the plenum case. With the increase of blowing ratio, the film coverage difference becomes smaller between different rib orientation cases. The 45° rib case also produces a higher heat transfer coefficient, which is higher than the 135° rib case by 3.4–8.7% within the studied blowing ratio range. The discharge coefficient of the 45° rib case is the lowest among the three cases. The helical motion of coolant flow is observed in the hole of the 45° rib case. The jet divides into two parts after ejecting out of the hole due to this motion, which results in the strong velocity separation and loss. For the 135° rib case, the vortex in the upper half region of the secondary-flow channel rotates in the same direction with the hole inclination direction, which leads to the straight streamlines and thus results in lower loss and higher discharge coefficient.

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1. Introduction

In order to further improve thermal efficiency as well as thrust for gas turbine engine, the increase of turbine inlet temperature is an effective method. Correspondingly, the turbine blades experience very high heat load, which may result in material failure due to higher temperature and thermal stress. A series of available cooling techniques to prevent turbine blades from overheating are introduced as shown in Fig. 1. The actual blades use combination of internal cooling in the inter channels and external film cooling on the outer surface. During past decades, most studies have focused on either internal or external cooling, neglecting their interactions. Because of this, the research on the methods, integrated internal and external cooling impact, has a broad prospect. The study aims at the effects of the inclined ribs on both of internal flow structure in film hole and the film cooling on outer surface.

In the internal cooling research, increasing heat transfer coefficient and heat exchange area are the two main directions of internal cooling technology. Generally, the inclined ribs are used in the internal cooling of turbine blades. They can enhance the flow disturbance through the process of separation and reattachment, which evidently enhances the heat transfer between the fluid and surface. Experimental measurements and numerical simulations of the ribs studies [1–5] confirm that the flowfield and heat transfer highly depend on the flow conditions and rib parameters, such as rib shapes, height, spacing, channel aspect ratio, length-to-diameter ratio, etc. According to lots of relative researches, the results show that both of flow Reynolds number and geometric parameters observably affect the heat transfer performance. Recently, Wang et al. [6] report the influences of rib configurations

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Nomenclature

C_d	discharge coefficient
d	hydraulic diameter, [m]
D	film hole diameter, [m]
h	heat transfer coefficient, [W/m^2 K]
M	blowing ratio, $=\rho_c U_c/\rho_g U_g$
m	mass flow rate, [kg/s]
P	pressure, [Pa]
Re_g	mainstream Reynolds number, $=\rho_g U_g D/\mu_g$
Re_c	coolant channel Reynolds number, $=\rho_c U_c d/\mu_c$
T	temperature, [K]
U	velocity, [m/s]
X	the mainstream flow direction, [m]
Y	the lateral direction, [m]
Z	the height direction, [m]

Greek symbols

α	rib orientation, [°]
β	inclination angle relative to main-flow direction, [°]
γ	inclination angle relative to cross-flow direction, [°]
η	film cooling effectiveness, $=(T_{aw}-T_g)/(T_c-T_g)$
ρ	density, [kg/m^3]
λ	thermal conductivity, [W/m K]
μ	dynamic viscosity, [N s/m^2]
Θ	non-dimensional temperature, $=(T-T_g)/(T_c-T_g)$

Subscripts

aw	adiabatic wall
c	coolant flow
f	film coverage
g	hot gas or mainstream
w	wall surface
κ	adiabatic exponent
s	surface
0	without injection

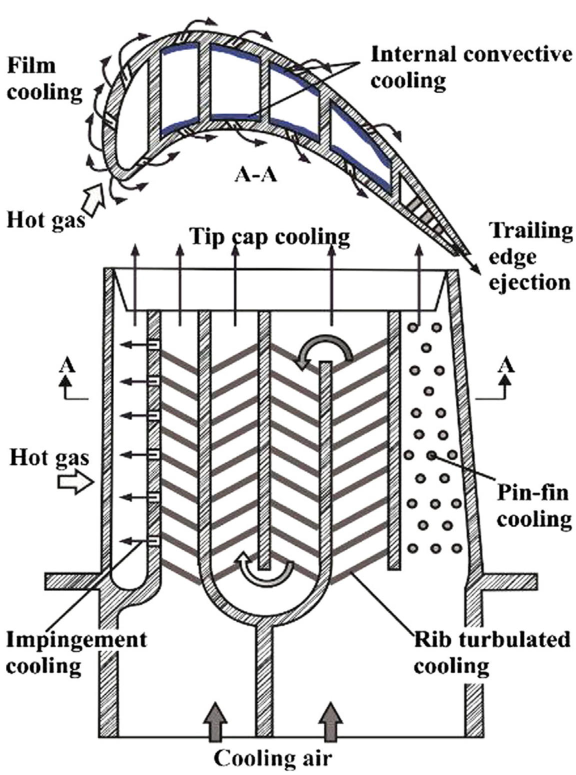

Fig. 1. Typical cooling techniques for turbine blades.

on adiabatic film cooling effectiveness by numerical simulation. The results showed that circular rib configuration without truncation provides a higher cooling effectiveness relative to square rib. Further, different rib angles lead to different effects of flow suction. With respect to rib orientation, Han's researches [7] show that 45° inclined rib case has higher heat transfer performance compared with 90° inclined rib case at same coolant flow condition. Experimental measurement of the heat transfer performance in a two-pass rectangular channel with various inclined rib arrangements by Azad et al. [8] confirmed that the 45° inclined parallel-ribs case provides a higher heat transfer enhancement relative to the ±45° inclined cross-ribs case. It is interesting that Liou et al. [9] compare the flow patterns and turbulence parameters between different rib orientations (45°, −45° and 90°) in a two-pass ribbed-wall parallelogram channel with the 180° sharp turn. The 45° and −45° ribs induce counter-rotating longitudinal vortex pair which strengthen the inlet generated secondary-flow in the first pass and the 180° sharp turn generate a secondary-flow in the second pass, respectively. Park et al. [10] investigate the combined effects of the channel aspect ratio and rib orientation angles on heat transfer and pressure drop in rectangular channels with two opposite ribbed walls. The corresponding rib orientation angles are 90°, 60°, 45° and 30°, respectively. The results suggest that the 60°/45° inclined ribs provide the best heat transfer performance for the square channel. For the narrow aspect ratio channel, the 45°/60° inclined ribs are recommended, while the 30°/45° inclined ribs are better for wide aspect ratio channels.

The difference with the internal cooling or film cooling separately is that the investigations on the effect of internal cooling on film cooling performance are limited. For instance, Wang [6] analyzes the effects of rib configurations and velocity ratios on film cooling. However, the focus is the heat conduction with consideration of the combination of internal cooling and external cooling. Peng [11] studies the influence of cross-flow channel on film cooling effectiveness for various film hole configurations, including cylindrical, trenched and fan-shaped holes. Corresponding result shows that film cooling effectiveness of the cross-flow coolant model is larger than that of the plenum model for the cylindrical and trenched holes. The simulation results by Agata et al. [12] indicate that the rib orientation significantly affects the temperature and flow structures in the downstream region of the hole and thus affects the film cooling performance. Bunker and Bailey [13] experimentally research the influence of rib on the discharge coefficient for the turbulated and baseline smooth passage. Alignment of the hole entry which is respect to the turbulator is shown to have a substantial effect on the discharge coefficients. The suction of the hole also leads to the change of internal flow characteristics. Experimental studies by Shen et al. [14] indicate the introduction of the film holes significantly reduces the degree of separation in each rib downstream. The area-averaged heat transfer coefficient is higher than that of traditional ribbed surface by 25%.

With respect to film cooling for turbine blades, previous studies mainly analyze the influence of different aerodynamic parameters

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