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Research Paper

Experimental investigations on the effects of inclination angle and blowing ratio on the flat-plate film cooling enhancement using the vortex generator downstream

Liming Song, Chao Zhang, Yingjie Song, Jun Li *, Zhenping Feng

Institute of Turbomachinery, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- The impact of VG on film cooling effectiveness is investigated experimentally.
- The flow mechanism of VG enhancing film cooling performance is clear visualized by PIV system.
- The effect of blowing ratio on the flow mechanism and film cooling effectiveness is studied.
- The effect of inclination angle on the flow mechanism and film cooling effectiveness is studied.

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ABSTRACT

Experimental studies were carried out to study the effects of inclination angle ($\alpha = 20^\circ, 30^\circ, 40^\circ$) and blowing ratio ($M = 0.5$, 1.0, 1.5) on the vortex generator (VG) to enhance the film cooling performance in a flat plate. Clear vortical structures visualized by Particle Image Velocimetry (PIV) system showed that an anti-counter-rotating vortex pair (ACRVP) was generated by VG. The secondary flow was entrained towards the wall and spread laterally because of the downwash effect of the ACRVP. The VG significantly improved the film cooling effectiveness. Especially when $\alpha = 20^\circ$, $M = 1.5$, the area averaged film cooling effectiveness was improved as much as 248% by using VG. For the cases with VG, as the blowing ratio increases, the film cooling effectiveness increases in those cases with $\alpha = 20^\circ, 30^\circ$ due to the strong downwash effect of ACRVP. In the case with $\alpha = 40^\circ$, the film cooling effectiveness was enhanced with the increase of the blowing ratio when $M < 1$, due to the strong downwash effect of ACRVP. However, when $M > 1$, the film cooling effectiveness decreased because the upward momentum of the secondary flow was so high that its flow rate exceeded the entrainment capacity of ACRVP, worsening the film attachment on the wall.

1. Introduction

High thermal efficiency and power output is the ultimate goal of gas turbine design, and the greatest contribution is made by raising the turbine inlet temperature. Nowadays, the inlet temperature of advanced gas turbine has exceeded the melting point of turbine blade materials, therefore, sophisticated cooling technologies, such as internal cooling, impingement cooling, film cooling and combined cooling technologies, have been applied to lower down the blade temperature so as to ensure a long service time and operation safety [1,2]. Among those technologies, film cooling has been one of the most important cooling techniques for decades. Goldstein [3], Bogard et al. [4] and Han et al. [5] reviewed research achievements of film cooling in experiments and numerical computations over the last half century, and concluded that film cooling performance could be affected by various parameters, such as inclination angle of the coolant hole, blowing ratios, mainstream turbulence and blade surface curvature.

The film cooling structure is intrinsically an inclined jet in a cross-flow (JICF). Abundant studies, both numerical researches (Fric and Roshko [6], Leylek and Zerkle [7], Tyagi and Acharya [8]) and experimental studies (Kelso and Perry [9], Blanchard et al. [10]), have explored the nature of JICF. These research results show that the typical feature of JICF affecting the film cooling performance is the counter-rotating vortex pair (CRVP) in the jet, namely, the so-called kidney-shaped pair of vortices. They are generated by the round jet when it penetrates into the crossflow. The

* Corresponding author.
E-mail address: junli@mail.xjtu.edu.cn (J. Li).

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Nomenclature

Symbols

D	diameter of the film cooling hole [mm]
DR	coolant-to-mainstream density ratio
M	blowing ratio
T	temperature [°C]
Tu	mainstream turbulence intensity
U	velocity component perpendicular to the wall [m/s]

Greek symbols

α	the inclination angle, angle between the film cooling hole and mainstream
ρ	density [kg/m^3]
λ	thermal conductivity [W/(m K)]
η	adiabatic film cooling effectiveness

Subscript

avg	average value
area	the whole measured wall surface, $1 \leqslant X/D \leqslant 19, -3 \leqslant Y/D \leqslant -3$
f	secondary flow
m	mainstream
spanwise	direction parallel to Y direction
streamwise	direction parallel to X direction
w	the adiabatic wall

Acronyms

ACRVP	anti-counter-rotating vortex pair
CRVP	counter-rotating vortex pair
CTA	constant temperature anemometer
PIV	particle image velocimetry
VG	vortex generator

CRVP imposes the upwash effect on the jet and promotes the lift-off tendency of the jet. Hence, how to cripple or suppress the strength of the CRVP has become the challenge in enhancing film cooling performance.

The shaped hole, an exit hole shaped like a diffuser other than the ellipse, is the only major advancement which has been realized in industry. Bunker [11] reviewed the development of shaped film cooling technology and summarized that a better attachment and lateral spreading of the coolant would be achieved compared with traditional round hole. Besides, film cooling performance of shaped hole was little susceptible for blowing ratio and turbulence intensity of mainstream. Haven et al. [12] investigated the vortical structure of three shaped holes and found that anti-kidney pairs were generated, leading to a better jet attachment whatever the condition was. Considering the tremendous impact of exit hole shape, various novel hole designs were put forward, such as sharp edged diffuser hole [13], leaf-shaped hole [14] and trench hole [15].

In addition, various technologies for enhancing cooling effectiveness have been studied. Heidmann and Ekkad [16] put forward the "anti-vortex" film cooling hole concept – two side holes were drilled intersecting with the main hole, which effectively counteracted the detrimental vorticity associated with standard circular cross-section film-cooling holes. Furthermore, various novel hole designs were put forward, such as the sister hole structure. A numerical analysis was conducted by Ely and Jubran [17] on sister holes by using cylindrical holes with 55 inclination angle. Their results showed that the sister holes dramatically suppressed CRVP, resulting in the significant improvement in film cooling effectiveness. Wu et al. [18] applied Thermochromic Liquid Crystal (TLC) technique on analyzing the effects of side hole position and blowing ratio in film cooling performance, and found that the side holes could improve the film cooling performance by repressing the CRVP intensity of the main hole, and the downstream sister hole performs best at blowing ratio from 0.3 to 2.5. Besides, Kusterer et al. [19] introduced the Double-Jet Film Cooling (DJFC) technology through hole geometry, and established an anti-kidney vortex pair in the DIFC. Furthermore, Kusterer et al. [20] developed a Nekomimi ("cat ears") technology which is suitable for fabrication derived from the DJFC technology.

Recently, many attempts on enhancing the film cooling performance through various flow control devices at the upstream or downstream of the film cooling hole are carried out, hoping to generate opposite vortex pairs to eliminate the negative effects of the CRVP. Na and Shin [21] placed a step ramp facing backward at the upstream of the hole. The effects of the angle and sharpness of the ramp were investigated by numerical simulation. The results showed that the geometric modification changed the position of the interaction of boundary layer and coolant, eliminated the horseshoe vortex, resulting in a broad lateral extension, thus improved the film cooling effectiveness by two times or more. Sakai [22] experimentally studied the ribs installed in the secondary flow channel and three types of rear bumps in the downstream of the hole in detail. It was showed that a longitudinal vortex generating downward velocity component was formed at the trailing edge of the cylindrical bump, improving the film cooling performance. Funazaki et al. [23] put base-type double flow-control devices (DFCDs) at the upstream of the film cooling hole in a flat plate and achieved an enhancement in effectiveness. A research of DFCDs on the turbine blade was carried out recently by Kawabata et al. [24].

The vortex generator (VG) geometry, referred to as a microramp at times, has been recently addressed for boundary-layer flow control, such as the control of supersonic oblique shock applied by Babinsky et al. [25]. Rigby and Heidmann [26] first attempted to put the VG downstream and found that the design could cancel the upwash CRVPand generated the downwash anti-kidney vortex pair downstream through the numerical study. Zaman et al. [27] conducted an experiment on the effects of the height, location and radius of VG in preventing lift-off of a jet in crossflow, which demonstrated detailed flow field properties. Furthermore, Shinn and Vanka [28] performed the large eddy simulation on film cooling flows with VG and found that the flow mechanism of VG is to generate near-wall counter-rotating vortices, which is helpful in entraining coolant from the jet and transporting it to the wall.

It is indicated in the previous works that VG shows an advantage of high film cooling effectiveness. However, there is a lack of detailed film cooling effectiveness distribution measurements in previous researches. Besides, as for the scope of authors, no one in their experimental studies has considered the effect of inclination angle on VG for enhancing the film cooling effectiveness. It's of great importance to conduct more systematic and in-depth researches on VG concept. Therefore, in this work, a wind channel platform was built to study the impact of blowing ratio, as well as the inclination angle on VG to enhance the film cooling effectiveness. Three cases with VG at different inclination angles and other three cases without VG at different blowing ratios of M = 0.5, 1.0, 1.5, 18, were experimentally investigated in the current study. In