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Effects of compound angle on film cooling effectiveness with different streamwise pressure gradient and convex curvature

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ABSTRACT

Streamwise pressure gradient and surface curvature are two important characteristics of turbine flow and compound angle film cooling is an efficient way to improve cooling performance. Compound angle film cooling effectiveness with those two effects was investigated using PSP technology. The corresponding numerical studies were validated and carried out to investigate the physical mechanism of the interaction between the coolant jet and the main flow. Compound angle increases film cooling effectiveness for high blowing ratios in the near hole region, but the stronger interaction between the jet and the main flow makes the coolant dissipate faster. On the flat surface, the favorable pressure gradient leads to a maximum of 50% increase of film cooling effectiveness compared with the adverse pressure gradient case. On the convex surface, the cooling jet is pushed to the wall by the radial pressure gradient in the free stream which makes film cooling effectiveness 20–50% higher than the flat wall case. The compound angle film cooling performance under strong favorable pressure gradient for the convex surface is quite different from the flat wall case and thus streamwise pressure gradient and surface curvature should be taken into consideration in gas turbine film cooling design.

1. Introduction

In modern gas turbine design, higher turbine inlet temperature is desired as to increase the efficiency and output of the machine. The hot gas path components must be cooled actively. Film cooling is one of the most important and commonly used cooling technologies.

Film cooling has been widely studied in the past 40 years. Most of them were conducted on flat plat test rigs. The review by Bogard and Thole [1] summarized plenty of geometries and flow parameters influencing film cooling performance, including blowing ratio, density ratio, and the three factors that we mainly focus on in this paper, film hole compound angle, wall curvature and streamwise pressure gradient (SPG). Compound angle is introduced into modern film cooling design to increase the lateral spreading of the coolant. It has been proved to be a sufficient way to keep coolant attached to the wall and has been widely used in gas turbine cooling design. As the capability of aerodynamic design and optimization of turbine airfoil increases, the interaction between film cooling jet and turbine main flow becomes more and more significant. The film cooling performance in turbine environment differs from that in the flat plate condition. Wall curvature and streamwise pressure gradient are two important characteristics of the turbine main flow.

Most of the previous studies on compound angle film cooling are conducted on flat plates. Leylek et al. [2] did a detailed analysis on the flow physics of compound angle film cooling and found that the kidney vortex pair transforms into a single large vortex for compound angle film cooling. Adiabatic film cooling effectiveness was investigated by Bogard et al. [3] and Ekkad et al. [4]. Both of their studies show that film cooling effectiveness is higher for compound angle injection than simple angle injection. Ligrani et al. [5–10] systematically investigated compound angle film cooling with different arrangements and found a significant improvement over simple angle configurations. Kusterer et al. [11] developed a double-jet film cooling system which is a combination of two neighboring compound angle film cooling holes and shows an improvement of film cooling effectiveness. Several works are done on cascade test rigs by Zhang et al. [12], Han et al. [13], and Walters et al. [14] and show that film cooling with compound angle has quite different cooling performance compared to the simple angle case.

Streamwise pressure gradient and wall curvature were mostly investigated separately in the previous studies. Launder and York [15] reported that strong favorable pressure gradient (FPG) improves film cooling effectiveness while reduces the lateral

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Nomenclature

Symbols

C	oxygen concentration
CA	compound angle
D	hole diameter
DR	density ratio ρ_c/ρ_∞
K	acceleration parameter
L	hole length
LI	light intensity
M	blowing ratio $\rho_c V_d/\rho_\infty V_\infty$
Ma	Mach number
P	pressure
(P_{O2})	partial pressure of oxygen
r	radius of curvature of the convex wall
Re	Reynolds number
S, R, Z	streamwise, wall normal and spanwise direction in convex wall case
T	temperature
u	velocity component in streamwise direction
V	velocity magnitude
W	molecular weight
X, Y, Z	streamwise, wall normal and spanwise direction in flat wall case
α	inclined angle
η	film cooling effectiveness
ν	kinematic viscosity
ρ	density

Subscripts

0	reference
aw	adiabatic wall
c	coolant condition
d	hole diameter
mix	mixture condition
r	recovery
∞	main stream condition

Abbreviations

AAEV	algebraic anisotropic eddy viscosity
APG	adverse pressure gradient
CVP	counter rotating vortex pair
FPG	favorable pressure gradient
LES	large eddy simulation
PIV	particle image velocimetry
PSP	pressure sensitive paint
RPG	radial pressure gradient
SPG	streamwise pressure gradient

spreading simultaneously. Ligrani [16] investigated full-coverage film cooling with different FPG and found that film cooling effectiveness increases with larger FPG. Jessen et al. [17], Coletti et al. [18] has done flow visualization work on film cooling jet and got detailed coolant flow structure with different streamwise pressure gradients. They found that FPG enhances the kidney vortex pair and makes it closer to the wall. Konopka et al. [19] conducted a LES simulation on shaped hole film cooling with adverse pressure gradient (APG) which shows good agreement with the PIV result.

Investigations on the effects of wall curvature are listed below. Ito et al. [20] and Schwarz et al. [21,22] measured film cooling effectiveness on convex, flat and concave walls. It is shown in there results that under low blowing ratios, effectiveness is larger on convex wall, while under high blowing ratios, effectiveness is larger on concave wall. Lutum et al. [23,24] studied FPG on convex surface and found that FPG reduces cooling effectiveness. But no flow field information was shown to reveal the physical mechanism of the interaction between main flow and coolant jet. Also, only one streamwise pressure gradient was investigated in Lutum's study.

Research on the effect of SPG and wall curvature on compound angle film cooling is few and lack of detailed analysis on the interaction mechanism. The present study investigated the film cooling performance with different SPG on both flat and convex wall experimentally and numerically to show the combination of the two effects systematically. Since the film cooling performance on flat plate is quite different from the case with SPG and wall curvature which is the real situation in a turbine. The present results are useful in the design of gas turbine cooling system.

2. Experimental facilities and procedures

2.1. Test facilities

Film cooling experiments were conducted on the plate film cooling test facility built in Tsinghua University. A schematic of the test rig is shown in Fig. 1. The main flow was supplied by an 11 kW centrifugal blower. The mainstream velocity was measured by a three-hole total pressure probe and a static pressure sensor, and controlled by a valve. The turbulence intensity upstream of the injection point was 2%. CO_2 and N_2 were used as the cooling gas to achieve a coolant to free stream density ratio of 1.52 and 0.97, respectively. The coolant flow was measured and controlled by a mass flow controller which had an uncertainty of 2%. Film cooling effectiveness was measured by pressure sensitive paint based on mass and heat transfer analogy. More detailed information of the test rig was described by Han [25].

The parameter used to characterize the SPG is the acceleration parameter K defined as:

$$K = \frac{\nu_\infty}{u_\infty^2}\frac{\partial u_\infty}{\partial x} \quad (1)$$

The test section of flat and curved wall and the detailed geometry of film cooling hole are shown schematically in Fig. 2. Different mainstream K can be achieved by applying different main flow pass converging ratio which is the height of the outlet divided by

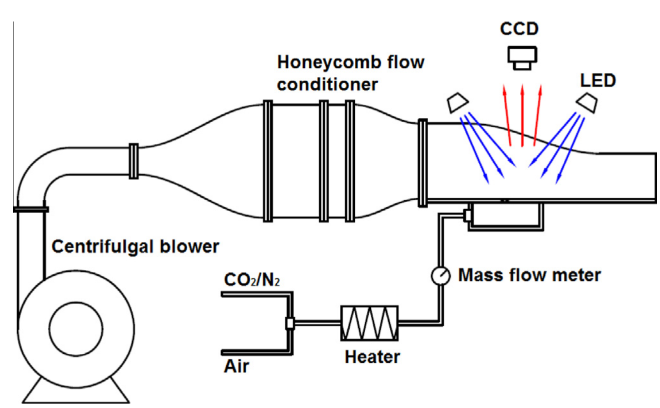

Fig. 1. Sketch of the test facility.