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Experimental Study of Film Cooling Behaviors at a Cylindrical Leading Edge

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Abstract

Dispersion of coolant jets in a film cooling flow field is the result of a highly complex interaction between the film cooling jets and the mainstream. In order to investigate the effect of blowing ratios on the film cooling of turbine blade, cylindrical body model was used. Mainstream Reynolds number based on the cylinder diameter was 7.1×10^4. The free-stream turbulence intensity kept at 5.0% by using turbulence grid. The effect of coolant flow rates was studied for blowing ratios of 0.9, 1.3 and 1.6, respectively. The temperature distribution of the cylindrical model surface is visualized by infrared thermography (IRT). Results show that the film-cooling performance may be significantly improved by controlling the blowing ratio. As blowing ratio increases, the adiabatic film cooling effectiveness is more broadly distributed and the area protected by coolant increases. The mass flow rate of the coolant through the first-row holes is less than that through the second-row holes due to the pressure variation around the cylinder surface.

Key Words : Film Cooling, Turbine Blade, Blowing Ratio, Film Cooling Effectiveness, Infrared Thermography

NOMENCLATURE

B	blowing ratio
D	diameter of cylindrical leading edge
d	diameter of cylindrical injection hole
L	length of coolant passage
Re_D	Reynolds number based on the cylinder diameter
T	temperature
U	velocity
X	streamwise distance measured from turbulence grid location

Greeks

α	streamwise injection angle from stagnation line
β	lateral injection angle
η_{aw}	adiabatic film cooling effectiveness
ρ	density

Subscripts

aw	adiabatic wall
c	coolant
t	turbulent
∞	mainstream

1. Introduction

From a thermodynamic cycle analysis, it was found that the thermal efficiency of gas turbine engine can be improved by increasing turbine inlet temperature (TIT), and TIT has been continuously increased over the past several decades. Therefore, turbine blade has to be protected from combustion gas with very high temperature, which may be above the melting point of turbine blade materials. In a film cooling system of turbine blade, the coolant air extracted from compressor before entering combustion chamber is injected into mainstream through discrete holes drilled along the blade surface. To develop the high efficient gas turbine engine, designers and researchers are trying to get greater cooling performance from less coolant air.

Many experimental and computational studies have been carried out. Goldstein (1) reviewed on the subject of film cooling technology until 1971. For experimental studies, Goldstein *et al.* (2) were the first to pioneer the use of shaped injection hole for improving film cooling performance. They used a shaped injection hole with 10^0 spanwise-diffused hole exit and found that the shaped injection hole provides better film cooling characteristics than cylindrical one, because of the attenuated coolant lift-off from surface. Thole *et al.* (3) measured the flow fields of three different injection holes, which were a cylindrical hole, a laterally diffused hole and a forward-laterally diffused hole. The results of their study showed that by diffusing the hole exit, both the penetration of the coolant into mainstream and the intense shear regions are significantly reduced relative to a cylindrical injection hole. Reiss & Bolcs (4) used a cylinder model to investigate the film cooling characteristics of shaped injection holes with diffused exit in the leading edge. They revealed that the shaped injection holes have better film cooling characteristics than cylindrical one. For computational studies, Thakur *et al.* (5) analyzed the characteristics of a blunt body leading edge film cooling using low Reynolds number $k-\varepsilon$ turbulence model.

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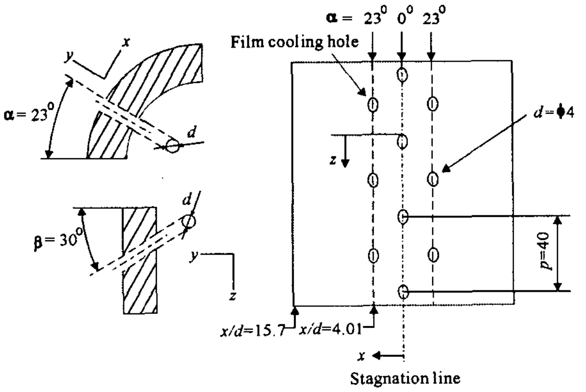


Fig. 1 Overview of showerhead geometries.

They proposed that CFD (Computational Fluid Dynamics) could be used to design optimum film cooling system by analyzing the effects of variation of streamwise injection angle and injection hole arrangement. Using $k-\omega$ shear-stress transport (SST) turbulence model, Lin *et al.* (6) investigated the three-dimensional flow and heat transfer about a semi-cylindrical leading edge with a flat afterbody. Bohn *et al.* (7) conducted a numerical analysis for a real turbine blade cascade having film cooling holes in the leading edge with streamwise and lateral injections. Kidney vortices appeared downstream of injection hole in the streamwise injection case and asymmetric vortices appeared in the lateral injection case. In recent years, a series of numerical analyses on streamwise injection with cylindrical holes (8), compound-angle injection with cylindrical holes (9), streamwise injection with shaped holes (10) and compound-angle injection with shaped holes (11) have been conducted. They revealed detailed film cooling physics and studied the effects of various shaped injection holes and injection angles systematically.

In this study, the effects of blowing ratios on the leading edge film cooling were investigated by using cylindrical body model. Also, the temperature distribution of the cylindrical body surface is visualized by infrared thermography (IRT).

2. Efficiency of Film Cooling

The adiabatic film cooling effectiveness can be written as follows:

$$\eta_{aw} = \frac{T_{aw} - T_\infty}{T_c - T_\infty} \tag{1}$$

When η_{aw} is 1, the adiabatic wall temperature is same with the coolant temperature. This means that the surface is perfectly protected from mainstream by coolant. When η_{aw} is 0, the adiabatic wall temperature is same with the mainstream temperature. This means that the surface is not protected from mainstream by coolant any more.

Blowing ratio B is one of important parameters in film cooling study. It is represented as the mass flux ratio between the mainstream and the coolant as follows:

$$B = \frac{\rho_c U_c}{\rho_\infty U_\infty} \tag{2}$$

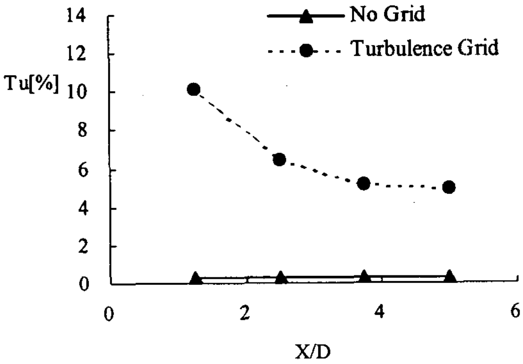


Fig. 2 The distributions of the averaged free-stream turbulence intensity along the streamwise direction.

3. Experimental Facilities and Techniques

The cylindrical model for simulating turbine blade leading edge is shown in Fig. 1. The showerhead configuration consists of three staggered rows of cylindrical holes with a leading edge diameter of D = 80mm. They are arranged symmetrically with respect to the free jet flow, at streamwise direction 0° and ± 23°, and a hole spacing of p/d = 10. Length-to-diameter ratio (L/d) is 4.62. Also, α and β denote the streamwise and lateral injection angles, respectively. The coordinate system used is such that the x-axis is streamwise direction along the surface, the y-axis is normal direction to the cylindrical body surface and the z-axis is lateral direction along the surface.

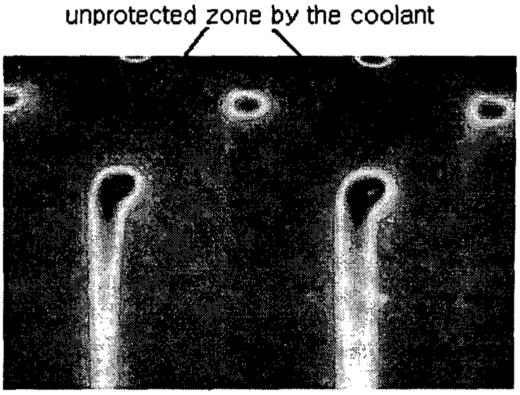
Subsonic wind tunnel has contraction ration of 7:1 and its maximum velocity and turbulence intensity are 45m/s and about 0.2%, respectively. The spatial uniformity of average velocity is about ±1% except boundary layer region. A honeycomb and four screens are installed in it for supplying uniform mainstream. The cross-sectional area of acrylic test section is 450mm x 450mm and its length is 4.3m. The free-stream turbulent intensity is measured by 1-axis hot wire probe of IFA 300 (TSI). Auto traverse system was used to control the exact position of the probe.

A turbulence grid is used to elevate a free-stream turbulence intensity, which is placed at 5×D upstream of the cylindrical model. The wire diameter of turbulence grid is 10mm and its mesh width is 50mm. Figure 2 shows the distributions of the averaged turbulence intensity along the streamwise direction. It is seen that with turbulence grid the free-stream turbulence intensity at X/D≈5 is about 5%. Mainstream velocity is measured by pitot probe connected to a micromanometer. The secondary flow supply system that supplies coolant consists of heating blower, orifice type flow meter and pipe. Heating blower contains sirocco fan, heater and automatic temperature controller. Coolant flow rates are adjusted until the desired blowing ratio, B, in Eq. (2) by controlling the flow meter. A T-type thermocouple is located around injection hole entrance in plenum and connected to automatic temperature controller to constantly maintain the desired coolant temperature. The cylindrical body model is made of polyacetal, which has low heat conductivity of 0.2-0.4 W/mK, to make the adiabatic surface and reduce the conduction effect as much as possible. A tailboard is placed at the rear of the cylinder to reduce wake effects on the upstream heat transfer. To calibrate the IRT, analyzing recorder, DA100 (YOKOGAWA), reads adiabatic wall temperature through T-type thermocouples at 20 points attached along the body surface. All thermocouple wires are extracted to the back of a cylindrical body model through plenum and connected to the analyzing recorder. The temperature distribution of the cylindrical body surface is measured by infrared thermography (IRT), VARIOSCAN 3011 (JENOPTIK). The spectral sensitivity of this camera is 8-12μm and the thermal resolution of this camera is ± 0.03K at 30℃ black-body radiator. The size of the image is 86400 pixels and frame repeat cycle is 0.9sec. The error on the measured temperature between the thermocouple and IRT depends strongly on the emissivity of the cylinder model surface. Therefore, the model was covered with a thin layer of a black paint that exhibits a high emissivity. The IR-camera used in this study showed a good accuracy of the temperature calibration the order of ±0.6℃ at 20 points attached along the body surface, which is considered negligible.

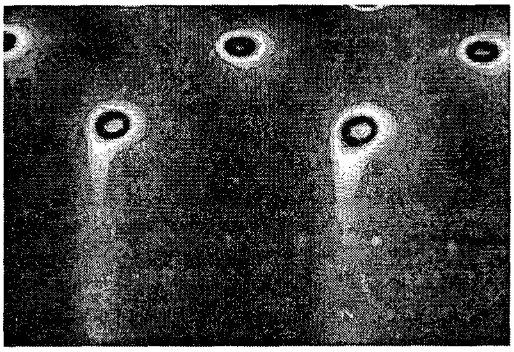
Mainstream velocity was fixed at 14m/s. Reynolds number based on D, Re_D, is about 71,000. We conducted experiment with three different blowing ratios, 0.9, 1.3 and 1.6, respectively. The coolant was heated 25℃ above the mainstream temperature and its temperature was constantly maintained by automatic temperature controller in heating blower.

4. Results and Discussion

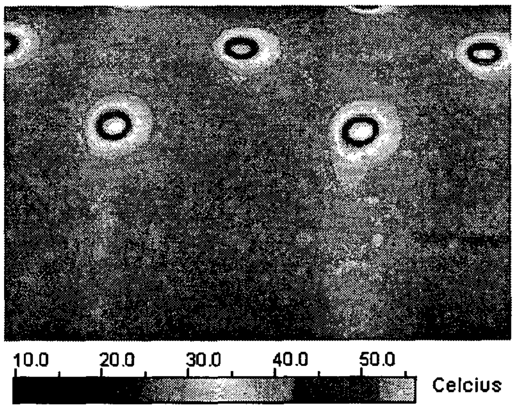
Figure 3 shows the surface temperature distributions at the leading edge surface measured by IR-camera. We can see good periodicity of the contours in the lateral direction and good symmetry in the stagnation zone. For higher blowing ratios, the coolant shows better coverage of the surface with the coolant film. When B=0.9, it is seen that the mass flow rate of the coolant through the first-row holes is less than that through the second-row holes. This is because the pressure near the exits of the first-row holes is smaller than that of the second-row holes. It can be seen also that the jet trajectory is sensitive to the blowing ratio. The streaks of the second-row get smaller as the blowing ratio increases. At the first-row holes, the coolant is more broadly distributed as the blowing ratio increases. For the case of B=0.9, we can see the unprotected zone by the coolant near the first-row holes.



(a) B = 0.9



(b) B = 1.3



(c) B = 1.6

Fig. 3 Surface temperature distributions at the leading edge surface with CH30.

Figure 4 shows local adiabatic film cooling effectiveness for different blowing ratios along the streamwise direction. At x/d=1.00 (near the first-row hole), the local adiabatic film effectiveness increases with an increase in the blowing ratio. However, at

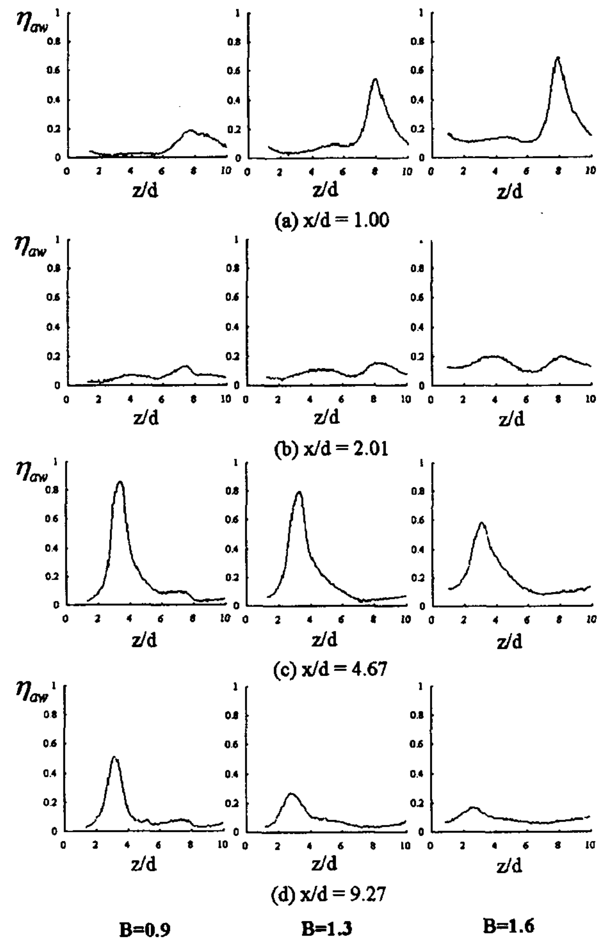


Fig. 4 Local adiabatic film cooling effectiveness for different blowing ratios.

x/d=4.67 (near the second-row hole), the local adiabatic film effectiveness decreases with an increase in the blowing ratio. Also, as blowing ratio increases, the adiabatic film cooling effectiveness is more broadly distributed and the area protected by coolant increases.

5. Concluding Remarks

In this study, we have conducted experimental analyses to investigate the effects of blowing ratios on the characteristics of turbine blade leading edge film cooling using cylindrical body model. Also, the temperature distribution of the cylindrical body surface is visualized by infrared thermography (IRT). Film-cooling performance may be significantly improved by controlling the blowing ratio. As blowing ratio increases, the adiabatic film cooling effectiveness is more broadly distributed and the area protected by coolant increases. The mass flow rate of the coolant through the first-row holes is less than that through the second-row holes due to the pressure variation around the cylinder surface.

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