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Film Cooling Performance of a Row of Dual-fanned Holes at Various Injection Angles

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Film cooling performance about a row of dual-fanned holes with injection angles of 30°, 60 ° and 90° were experimentally investigated at blowing ratios of 1.0 and 2.0. Dual-fanned hole is a novel shaped hole which has both inlet expansion and outlet expansion. A transient thermochromic liquid crystal technique was used to reveal the local values of film cooling effectiveness and heat transfer coefficient. The results show that injection angles have strong influence on the two dimensional distributions of film cooling effectiveness and heat transfer coefficient. For the small injection angle of 30 degree and small blowing ratio of 1.0, there is only a narrow spanwise region covered with film. The increase of injection angle and blowing ratio both leads to the enhanced spanwise film diffusion, but reduced local cooling ability far away from the hole. Injection angles have comprehensive influence on the averaged film cooling effectiveness for various x/d locations. As injection angles are 30 and 60 degree, two bands of high heat transfer coefficients are found in mixing region of the gas and coolant. As injection angle increases to 90 degree, the mixing leads to the enhanced heat transfer region near the film hole. The averaged heat transfer coefficient increases with the increase of injection angle.

Keywords: gas turbine; film cooling; dual-fanned hole; thermochromic liquid crystal technique

Introduction

One of the major techniques in improving thermal efficiency and increasing propulsion thrust of gas turbine engines is to raise the turbine inlet temperature. However, the rise of the turbine inlet temperature causes a series of problems, such as shortening the blade lifespan, increasing thermal failure etc. The applications of various cooling techniques are effective ways to solve the high temperature issues.

Film cooling is one of the key cooling techniques on the vane and blade. There are many geometrical and aerodynamic factors influencing film cooling performance such as hole shapes, injection angles, blowing ratios, turbulence intensities etc.[1]. In the last few decades, the advancement of film cooling technique has been focused on innovative designs in the hole geometry [2-4]. As the separation flow forming after entering into the film hole causes the non-uniform velocity of coolant, the local high velocity is easy to lift-off after penetrating into the gas[5]. The expanded exit can produce more uniform flow and reduced mixing strength, resulting in high film cooling effectiveness, especially at high blowing ratio [6-8].

The separation flow in the hole with laterally expanded entrance can be impaired and the aerodynamic loss can be reduced [9]. It implies that the flow in the

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Nomenclature

Re	Reynolds number $=\dfrac{\rho_\infty u_\infty d}{\mu_\infty}$	s	the number of pixels in spanwise direction
BR	blowing ratio $=\dfrac{\rho_c u_c}{\rho_{loc} u_{loc}}$	τ	time
η	film cooling effectiveness $=(T_g - T_{aw})/(T_g - T_c)$	**Subscripts**	
h	heat transfer coefficient $= q/(T_{aw} - T_w)$	ave	averaged
T	temperature	c	coolant
c	heat capacity	g	gas
u	velocity	aw	adiabatic wall
d	diameter of film hole	∞	of mainstream
q	heat flux	loc	local
Greek letters		w	wall
ρ	density	0	initial
λ	heat conductivity coefficient	i	at i pixel
μ	dynamic viscosity coefficient		

shaped hole is vital to film cooling performance. However, there is few data on film cooling performance of shaped hole expanded both inlet and outlet.

Yuen et al. [10, 11] studied film cooling performance of a single round hole at various injection angles. Film cooling effectiveness and heat transfer coefficient were measured by the steady state heat transfer method. The literature about injection angles on film cooling performance of shaped hole injection is not found. As the flow in the shaped hole is different from that in the round hole, influence of injection angles on film cooling performance must be different from round hole injection. As the transient measurement technology of liquid crystal can accurately get the high resolution temperature distributions of the cooled surface and get the detailed distributions of film cooling effectiveness and heat transfer coefficient, it is widely applied in film cooling study. In this paper, film cooling performance of dual-fanned holes with various injection angles were studied by thermochromic liquid crystal transient measurement technique. Two dimensional distributions of film cooling effectiveness and heat transfer coefficient were analyzed.

Experimental approach

Experiment set-up

The experiments were conducted in a low speed wind tunnel as shown in Fig.1. The main flow and coolant flow were provided by separate centrifugal blower. The main flow goes through a flow stabilizing section followed by a contraction section and a fast response mesh heater before entering the test section. Mesh heater provided an instantaneous temperature step to the main flow by adjusting voltage level. The sizes of test plate made by Plexiglas were 380mm×210mm×30mm. The liquid glue was filled in the joint gap between removable film hole plate and test plate to guarantee the surface smooth. A trip wire of a diameter of 1.5 mm was installed at 100 mm upstream of the hole exit center to keep fully developed turbulent boundary layer. After going through the float flow meter and air heater, the coolant flow was discharged bypass atmosphere and instantaneously came into the plenum by turning three-way solenoid valve at starting test.

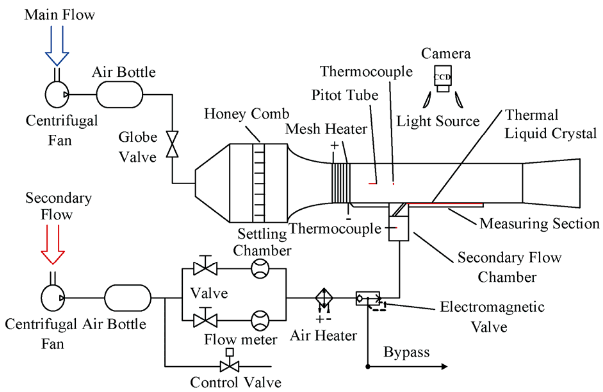

Fig. 1 Sketch of the test system

The velocity of main flow and turbulence intensity were measured by a hot-wire probe with a 10×5 array at measurement plane perpendicular to the mainstream, which was located at 10mm upstream of film hole exit center. The response frequency of hot wire was 2000Hz. The turbulence intensity is (1.2±0.04)% dependent on the measurement point. The temperatures of mainstream and coolant flow were measured by thermocouples. The temperatures of test plate surface were measured by thermochromic liquid crystal.

As shown in Fig. 2, a single hole row was composed of five film holes, which have the same cylindrical part with a diameter of 10mm. Three kinds of injection angles of 30°, 60° and 90° were tested to examine film cooling performance.

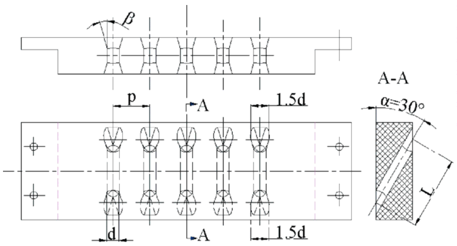

Fig. 2 Sketch of the dual-fanned hole

Measurement method

According to the semi-infinite body unsteady heat conduction of the third kind boundary condition:

$$\frac{T_w(\tau)-T_0}{T_\infty - T_0} = 1 - e^{\frac{h^2\tau}{\rho c\lambda}} \cdot erfc(\frac{h\sqrt{\tau}}{\sqrt{\rho c\lambda}}) \quad (1)$$

The characteristic temperature in film cooling is T_{aw}, that means:

$$T_\infty = T_{aw} = (1-\eta)T_g + \eta T_c \quad (2)$$

According to T_w, T_g and T_c, the double parameters of η and h can be solved.

For better color showing, a thin layer of black paint was sprayed onto the test wall as a substrate and a thin layer of the TLC was then air-brushed uniformly onto the black paint. CCD video camera took the image at rate of 25 frames at every second.

The blowing ratios of 1.0 and 2.0 were tested. The Reynolds number of mainstream was 12900.

Thermochromic liquid crystal calibration

TLC technique has evolved into an effective surface temperature and heat transfer coefficient measurement technique [12]. It is well established that using color space hue versus temperature by CCD camera RGB imaging and HSV (hue, saturation, value) color model post-processing. During calibration, a copper plate embedded with K-type thermocouples was sprayed with black paint and then with TLC. The current-conducting steel strip transferred heat to the cooper uniformly. The rate of TLC color change is dependent on the current intensity. In order to reduce the image noise and enhance image capture quality, camera was set to white balance mode [13]. To keep the condition compatible with real test run for the purpose of reducing uncertainties, the illumination intensity, angle and distance, camera location, TLC coating thickness were kept the same to the test section. Fig.3 shows the calibrated curves of liquid crystal.

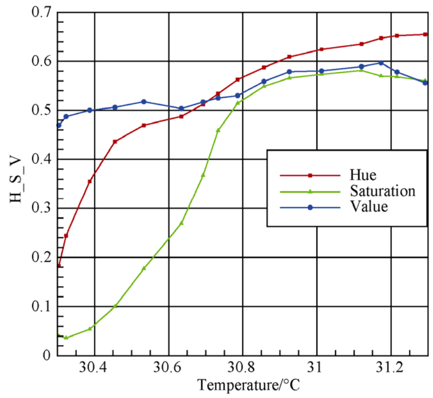

Fig. 3 Calibrated curves of liquid crystal of R30C1W

Uncertainty analysis

In the present transient liquid crystal measurement, the measurement uncertainties included temperature uncertainties: T_g, T_c, T_w and time uncertainty Dt in measurement T_g, T_c, T_w. The estimated uncertainty intervals for the present experiment were DT_g=DT_c=DT_w=0.2K and Dt=0.1 s. According to the uncertainty intervals given above, the relative uncertainties in heat transfer coefficient was about 8% and in local film cooling effectiveness was about 4% at 0.7. It should be noted that the measurement uncertainties vary with the heat transfer coefficient and adiabatic wall temperature and therefore are different at every position in the test surface.

Results and discussion

Local film cooling effectiveness

One spanwise period distributions of film cooling effectiveness with BR=1.0 are shown in Fig.4. The origin point of x ordinate is located at the center of film hole exit. The two dimensional distributions are strongly dependent on injection angles. As injection angle is 30 degree, the high film cooling effectiveness region is focused on the region at vicinity of center line downstream of film hole with spanwise film region of -1<y/d<1. Film cooling effectiveness decays slowly with the increase of x/d. This may be that the small injection angle leads to the attached flow of coolant after ejecting from the film hole and provides the relatively weak spanwise diffusion.

As injection angle is 60 degree, although the spanwise diffusion of film is better than the case of 30 degree, the values decrease rapidly with the increase of x/d, especially in the region of x/d>6. This may due to the gas entrains into the film sub-layer and causes strong mixing between the gas and coolant. The contour of film cooling effectiveness slightly deviates to the negative y axis direction because of the machining error of film hole. As injection angle is 90 degree, the coolant flow perpendicularly penetrates into the mainstream and causes more strong coolant diffusion in spanwise direction, leading to laterally homogeneous distribution of film cooling effectiveness, just like film cooling performance of slot injection. This can be attributed to the very little gas entraining into the film sub-layer.

Two dimensional distributions of film cooling effectiveness with BR=2.0 are shown in Fig. 5. For 30 degree injection, the more effective spanwise diffusion is found. The film with 60 degree injection diffuses quickly in spanwise direction. The film cooling effectiveness with 90 degree is significantly higher than the other two near the hole exit. This may be that the 90 degree injection with expanded exit takes a significant role in slot injection performance. The region near the hole exit is effectively covered with coolant film with very little gas mixing. Compared to the distributions of film cooling effectiveness for three injection angles, the small injection angle makes the coolant film flowing far away from the hole and the large injection angle makes the coolant film effectively diffusing spanwisely.

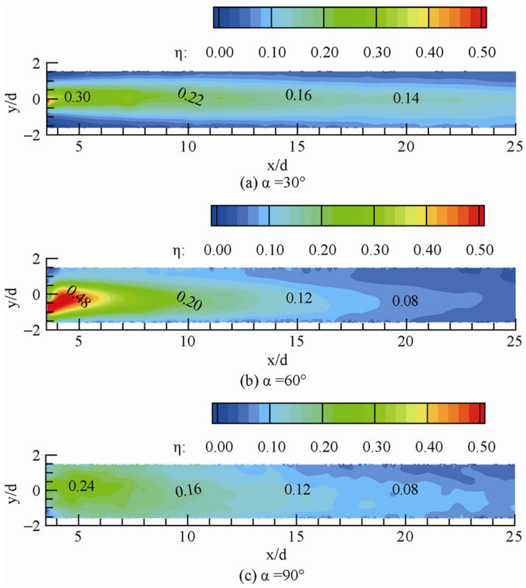

Fig. 4 Two dimensional distributions of film cooling effectiveness with *BR*=1.0

Local heat transfer coefficient

Two dimensional distributions of heat transfer coefficients with BR=1.0 are shown in Fig.6. Injection angles have strong influence on two dimensional distributions of heat transfer coefficients. As injection angles are 30 and 60 degree, two bands of high heat transfer coefficients are found in mixing region of the gas and coolant. As injection angle increases to 90 degree, because of the coolant flow perpendicularly penetrating into the mainstream, the mixing leads to the enhanced heat transfer region near film hole exit.

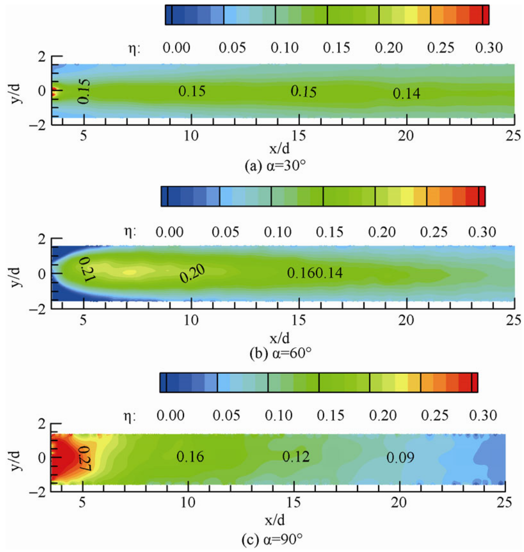

Fig. 5 Two dimensional distributions of film cooling effectiveness with *BR*=2.0

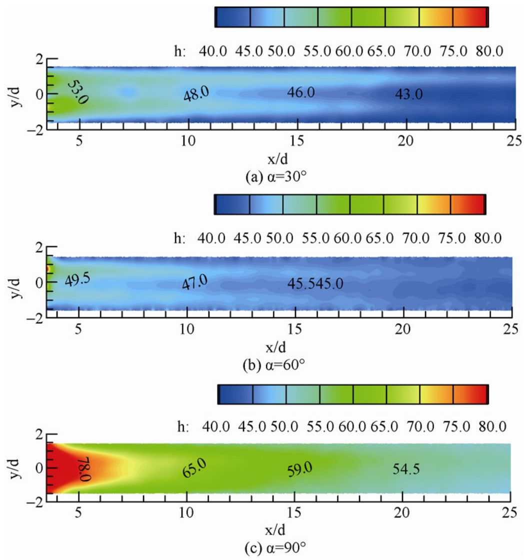

Fig. 6 Two dimensional distributions of heat transfer coefficients with *BR*=1.0

Two dimensional distributions of heat transfer coefficients with BR=2.0 are shown in Fig.7. Two bands of high heat transfer coefficients with 30 degree and 60 degree injections are found beyond x/d=15 and x/d=10. The spanwise distributions with 90 degree injection are similar with the case of BR=1.0 and BR=1.5. However, the heat transfer coefficients decays slowly in the mainstream direction.

Averaged film cooling effectiveness

The influence of injection angle on laterally averaged film cooling effectiveness is shown in Fig.8. Compared the data of Yuen in literature [8], film cooling effectiveness is significantly increased at the expanded hole, especially near the hole. At blowing ratio of 1.0, the laterally averaged values of 30 degree decrease slowly in the mainstream direction. The laterally averaged values of 60 degree and 90 degree decrease rapidly after increasing to the maximum values at x/d=5 and x/d=7 respectively. The decrease slope of 90 degree is smaller than that of 60 degree. In the region of x/d<16, the distributions of film cooling effectiveness are $\eta_{60°}>\eta_{90°}>\eta_{30°}$, while in the region of x/d>16, the distributions are $\eta_{30°}>\eta_{90°}>\eta_{60°}$. At the blowing ratio of 2.0, the laterally averaged values of 30 degree increase very slowly in the mainstream direction. The laterally averaged values of 60 degree decrease after increasing to the maximum value at x/d=8. The laterally averaged values of 90 degree decrease rapidly in the mainstream direction. In the region of x/d<15, the distributions are $\eta_{90°}>\eta_{60°}>\eta_{30°}$, while in the region of x/d>15, the distributions are $\eta_{30°}>\eta_{60°}>\eta_{90°}$.

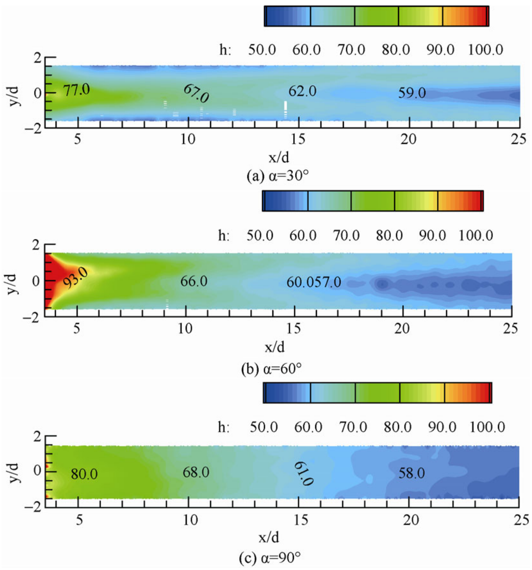

Fig. 7 Two dimensional distributions of heat transfer coefficients with *BR*=2.0

Averaged heat transfer coefficient

The influence of injection angle on laterally averaged heat transfer coefficients is shown in Fig.9. At blowing ratio of 1.0, the averaged heat transfer coefficients with 30 degree injection are lower than the values of the other two injection angles. This is likely to that the low blowing ratio and the small injection angle leads to the lower flow velocity of fluid downstream of the hole compared to no film cooling. The increase of injection angle leads to the raise of heat transfer coefficients. The close values of heat transfer coefficients with 60 degree and 90 degree injections are found beyond x/d=15 as the mixing flow

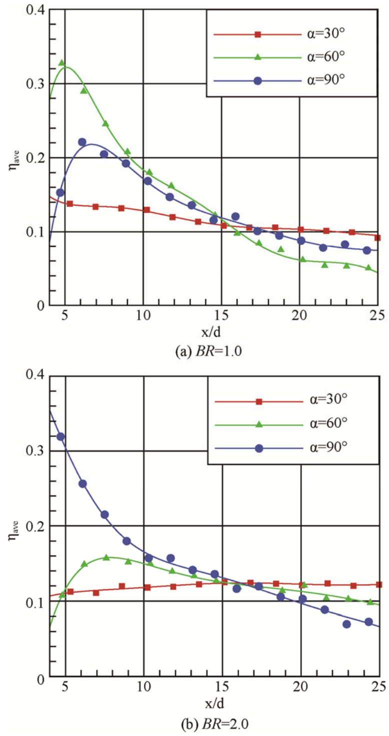

Fig. 8 Influence of injection angle on laterally averaged film cooling effectiveness

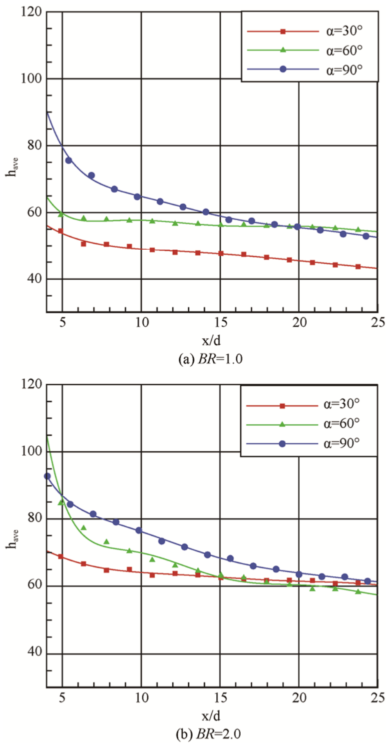

Fig. 9 Influence of injection angle on laterally averaged heat transfer coefficient

have become very weak. At blowing ratio of 2.0, the similar trend of heat transfer coefficient distributions was found. Beyond x/d=18, the heat transfer coefficient is very close for different injection angles. It implies that the influence of injection on averaged heat transfer coefficient is more significant and becomes very similar far away from the hole.

Compared to the averaged film cooling effectiveness and heat transfer coefficients, the advantage of film cooling for the small injection angle can be attributed to the low heat transfer coefficient. The advantage of film cooling effectiveness is not significant. The high film cooling effectiveness for the three injection angles is dependent on blowing ratio and the location of x/d.

Conclusion

Film cooling effectiveness and heat transfer coefficient for dual-fanned hole with injection angles of 30 degree, 60 degree and 90 degree were measured by transient TLC method. The two dimensional distribution of values were obtained.

Injection angles have strong influence on two dimensional distributions of film cooling effectiveness and heat transfer coefficient. For the small injection angle of 30 degree and small blowing ratio of 1.0, there is only a narrow spanwise region covered with film. The increase of injection angle and blowing ratio both leads to the enhanced spanwise film diffusion, but reduced local cooling ability far away from the hole. Injection angles have comprehensive influence on the averaged film cooling effectiveness for various x/d locations.

As injection angles are 30 and 60 degree, two bands of high heat transfer coefficients are found in mixing region of the gas and coolant. When injection angle increases to 90 degree, the mixing leads to the enhanced heat transfer region near the film hole. The averaged heat transfer coefficient increases with the increase of injection angle.

Acknowledgment

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