Cooling Performance for Cylindrical Film-Cooling Hole with Divided Downstream Crescent-Shaped Block

Pengfei Zhang\textsuperscript{1,2}, Zhiting Tong\textsuperscript{1,2}, Fei Wang\textsuperscript{1,2}, Linchao Bai\textsuperscript{1,2} and Chao Zhang\textsuperscript{1,2}

\textsuperscript{1} Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, Tianjin University of Technology, Tianjin, 300384, China
\textsuperscript{2} National Demonstration Center for Experimental Mechanical and Electrical Engineering Education, Tianjin University of Technology, Tianjin, 300384, China

Corresponding author: Chao Zhang, E-mail: czhangxj@163.com

Abstract. The cooling performances for the cylindrical film-cooling hole with divided downstream crescent-shaped blocks were numerically investigated in present study. Four configurations with divided crescent-shaped block, i.e. linear, 30° convergence, 30° expansion, and 30° curved expansion, were studied at typical flow conditions. The successive crescent-shaped block case and the no block case were also solved in comparison. The temperature profiles, the local and lateral averaged cooling effectiveness at blowing ratios of 0.5 to 1.5 were obtained. As compared with the successive block case, the lateral coolant coverage were widened by using the divided block, and thus the lateral averaged cooling effectiveness were improved, especially at higher blowing ratios. Comparatively, the cylindrical hole with 30° expansion crescent-shaped block exhibited highest cooling performance.

1. Introduction
At present, the inlet temperature of gas turbine is higher than the upper limit of bearing capacity of turbine blade. So, advanced turbine cooling technology can effectively improve turbine inlet temperature and cooling efficiency. Now, an effective cooling technology, film cooling, is being lucubrated. Film cooling is to protect the turbine blades by cold air jet ejected from the holes.

Film cooling effect is affected by many factors such as blowing ratio, hole shape and so on. Rigby et al.\textsuperscript{[1]} placed an eddy current generator downstream of the cylindrical hole. They found that the triangular eddy current generator could eliminate the upper kidney-shaped vortex and generate a new lower kidney-shaped vortex downstream. Khorsi et al.\textsuperscript{[2]} investigated adiabatic film effectiveness for film cooling by a cylindrical hole with and without the downstream short crescent-shaped block at different blowing ratios. Song et al.\textsuperscript{[3]} conducted experiments to study the effects of inclination angle and blowing ratio on the vortex generator to enhance the film cooling performance in a flat plate. Ji et al.\textsuperscript{[4]} used numerical simulation to study the effect of V-shaped block on the upstream of the film hole on the film cooling performance. An et al.\textsuperscript{[5]} placed the crescent block in the downstream position of the outlet of the cylindrical hole. They founded that this structure could effectively increase the transverse diffusion of cool air jet. Zhang C et al.\textsuperscript{[6]} studied the influence of the height of crescent block on the cooling effect. They founded that the performance of downstream film cooling was different at different block heights. This paper optimized the design of crescent hole based on the
research in literature [5]. We developed a new scheme of film hole, so as to find a better method to improve the cooling effectiveness.

2. Physical model and numerical setup

2.1 Physical model

The computational domain consists of a mainstream channel, a coolant plenum, a cylindrical hole and a crescent-shaped block downstream the hole. The cylindrical hole has a diameter \( D = 8 \text{mm} \), a lateral pitch of \( 3D \), and an inclination angle of \( 30^\circ \) with respect to the flow direction. In present study, a row of hole with periodic condition in lateral direction is simulated. The stream-wise length, and the vertical height of the mainstream channel are \( 51D \) and \( 15D \) respectively.

![Figure 1. Computational domain](image)

The front view of the cylindrical hole and the successive and divided crescent-shaped blocks are shown in figure 2. The stream-wise and lateral directions are denoted as coordinates \( X \) and \( Y \), respectively. The crescent-shaped block is placed away from the hole exit \( 0.5D \) downstream the cylindrical hole. The block has a height of \( 0.25D \), a width of \( 2D \), and a length of \( 1.5D \). The maximum distance between the leading edge and the trailing edge of the successive block is \( 0.5D \). In present study, four divided blocks, i.e. linear (case 3), \( 30^\circ \) convergence (case 4), \( 30^\circ \) expansion (case 5), and \( 30^\circ \) curved expansion (case 6), are proposed to improve the film cooling performance. The divided space in the lateral direction is \( 0.375D \). Besides, the cylindrical hole with no block (case 1) and with the successive block (case 2) are also studied in comparison.

![Figure 2. The cylindrical hole and the crescent-shaped blocks](image)

The polyhedral mesh is generated for the computational domain. The grid density of key positions such as the wall surface and cylindrical hole has been increased. The grid \( Y^+ \) value of the cooling wall surface is 0.92, which meets the requirements of the wall function.

2.2 Numerical setup and boundary conditions

The inlet speed of the mainstream is \( 15 \text{m/s} \). The total temperature is 450K. The static pressure at the outlet of the mainstream channel is 1 atm. The inlet temperature of the cooling jet is 326K. The
turbulence intensities at the mainstream channel inlet and the cooling jet inlet are set to 3.5% and 1% respectively. In the simulation process, the blowing ratio (M) is changed by changing the inlet velocity of the cooling jet. The definition of the film cooling effectiveness (η) as in equation (1):

$$\eta = \frac{T_g - T_w}{T_g - T_c}$$

(1)

Where $T_g$ is the inlet temperature of the mainstream channel, $T_c$ is the temperature of the adiabatic wall, and $T_c$ is the temperature of the cooling jet.

In this paper, CFD software is used for numerical calculation. The turbulence model is selected by k-ε model. The coupling of pressure and velocity is based on SIMPLE algorithm. In order to verify the correctness of the model, the calculation results of the crescent-shaped hole at M=1.0 are compared with the literature [4], and the results are shown in figure 3. It can be seen that the difference between the two groups of data is small, which proves that the calculation results obtained according to k-ε model are effective.

![Experimental data from An et al [5] compared with k-ε model](image)

Figure 3. Lateral-averaged effectiveness distributions at M=1.0

3. Results and analysis

3.1 Downstream temperature profile
A dimensionless temperature is defined as $\theta = 1 - \eta$, which showed in figure 4. For cylindrical hole, when $M=0.5$, the low temperature area is concentrated in the center of the wall, while the high temperature is on both sides. The crescent-shaped hole and other optimized hole all produce the kidney-shaped vortex. So the low-temperature area diffuses to both sides. When $M=1.0$, the temperature of the downstream of the cylindrical hole is high. However the crescent-shaped hole, especially for other four optimized hole, improves the distribution of cooling jet direction. When $M=1.5$, the temperature of the downstream of the cylindrical hole is high. Because the jet flow is significantly away from the wall surface. The improvement of crescent-shaped hole is limited. But the other four optimized hole structures further improve the spreading distribution of low temperature. Among them, 30° expansion hole structure has the best effect.
3.2 Local and lateral-averaged cooling effectiveness

As shown in figures 5, when $M=0.5$, adding turbulence structure, the transverse distribution of film cooling effectiveness on the wall surface is improved. When $M=1.0$, with the increase of blowing ratio, the film cooling effectiveness of all hole structures decreased. The addition of the spoiler greatly improves the film cooling effectiveness of the downstream wall position. The film cooling effectiveness of the four optimized hole structures is slightly better than that of the crescent hole, which is greatly improved compared with cylindrical hole. When $M=1.5$, with the further increase of the blowing ratio, the film cooling effect of the cylindrical hole almost disappears. This is because at a high blowing ratio, the cooling jet almost completely leaves the wall surface. So cooling jet unable to cover the wall effectively. Among the other five cooling structures, the film cooling effectiveness distribution of the optimized four cooling hole is better than that of the crescent hole. The 30° expansion hole show the best performance. Figures 6 show the lateral-average cooling effectiveness along the span at different $X/D$ of the downstream wall. When $M=0.5$, the lateral-average cooling effectiveness of the 30° expansion hole is the best. But when $X/D>10$, the cooling effect of five optimized hole structure is very close. When $M=1.0$, the average span-wise cooling effectiveness of 30° expansion hole and linear hole is the best and very close. But compared with cylindrical hole, it has been greatly improved. When $M=1.5$, the lateral-average cooling effectiveness of 30° expansion hole is obviously better than other hole.
Figure 6. Lateral-average film cooling effectiveness at different $M$: (a) $M=0.5$; (b) $M=1.0$; (c) $M=1.5$.

4. Conclusion

(1) With the increase of blowing ratio, the cooling effectiveness of cylindrical hole decreases obviously. Among them, the cooling effectiveness of 30° expansion hole is the best.

(2) Under the condition of high blowing ratio, the cooling effect of cylindrical air film hole decreased sharply. The improvement of crescent hole is very limited. Among them, 30° expansion hole structure has the best performance.

Acknowledgments

The authors would like to acknowledge the financial supports by Natural Science Foundation of Tianjin (Grant No. 18JCQNJC07200), Natural Science Foundation of China (Grant Nos. 51976139, 51516150).

References

[1] Rigby D L, Heidmann J D. Improved film cooling effectiveness by placing a vortex generator downstream of each hole[C], ASME Turbo Expo 2008: Power for Land, Sea, and Air. American Society of Mechanical Engineers, 2008: 1161-1174.

[2] Khorsi A, Guelailia A, Hamidou M K. Improvement of film cooling effectiveness with a small downstream block body[J]. Journal of Applied Mechanics and Technical Physics, 2016,
57(4).

[3] Song L M, Zhang C, Song Y J, Li J, Feng Z P. Experimental investigations on the effects of inclination angle and blowing ratio on the flat-plate film cooling enhancement using the vortex generator downstream[J]. Applied Thermal Engineering, 2017, 119.

[4] Ji K Y, Fei X Y, Zhang F, Zheng D R. Numerical Simulation of the Effect of Upstream V-Shaped Block on Film Cooling Performance[J]. Journal of Engineering for Thermal Energy and Power. 2017, 32(01):49-53+121.

[5] An B T, Liu J J, Zhang C et al. Film Cooling of Cylindrical Hole with a Downstream Short Crescent-Shaped Block[J]. Journal of Heat Transfer, 2013(135)031702-1.

[6] Zhang C, Wang Z. Effect of Downstream Crescent-Shaped Block height on Flat-Plate Film Flow and Cooling Performance [J]. Journal of Applied Mechanics and Technical Physics, 2018, 59(5): 951-961.