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Asymmetrical Compound-Angle on Combined-Hole Film Cooling

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ABSTRACT

In a modern gas turbine, a film cooling system was applied to provide thermal protection on the turbine components due to high turbine inlet temperatures. Enhanced film cooling effectiveness was formed through the combined-hole film cooling with various parameters. Due to limited research on the asymmetrical compound-angle, γ_1 / γ_2 on the combined-hole film cooling, the present work was worked on it. The effect of distance between two combined-holes in mainstream direction, LoD and different blowing ratio, M also covered in this work. All considered cases were simulated and the best arrangement of combined-hole film cooling will be determined. Based on different geometrical parameters; LoD and γ_1 / γ_2 applied, insignificant changes were observed. Meanwhile, a huge change was observed as the blowing ratio increase. As been observed, lateral coverage film cooling effectiveness was spread wider as blowing ratio increase but a drastic decrease of film cooling effectiveness was occurred at further downstream due to early separation and lift-off of the cooling air.

1. Introduction

Raising the turbine inlet temperature of a gas turbine is a major contributor to the increase in gas turbine performance. Due to very high temperatures, sophisticated cooling technologies were applied to protect the turbine components from extreme thermal loads which jeopardizing its durability. Among these cooling technologies, the film cooling system from discrete holes was introduced especially on the turbine blades to enhance thermal protection on the blade surfaces and ensure its reliability. The compressor bleeds air ejected through the film cooling hole will form a thin layer of cooled air on the blade surfaces and reduce the impact of hot mainstream air on the blade surfaces thus ensure lower heat transfer and temperature on the turbine blades. Film cooling

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has been extensively used and studied since the 1970s. Among the pioneers in this research field, Goldstein [1] provides the fundamental knowledge of film cooling. The cylindrical film cooling hole which known as the basic geometry of the film cooling hole is still being applied in a modern gas turbine due to its simplicity, low maintenance and manufacturability. Several studies [2-8] were carried out on the cylindrical film cooling hole and the discussion on the film cooling mechanism also had been provided. Most of the standard cylindrical hole produced narrow film cooling effectiveness coverage thus lowering the performance of the film cooling. Based on the idea to increase the film cooling effectiveness area of coverage, a method by applying an angle to the cylindrical hole was introduced. Several studies [8-11] had been covered experimental and numerically by applying an angle or known as a compound-angle to the cylindrical hole. The lateral spread of film cooling air was improved, however, it turned into one side. An asymmetrical counter-rotating vortex also formed with the increase of the compound-angle which fundamentally alters the interaction of the cooling air and mainstream air. To overcome the asymmetrical counter-rotating vortex, a combination of two cylindrical film cooling holes with opposite compound-angle was introduced and known as a combined-hole of film cooling. Some studies [5,8,12-16] had been done and reported that the combined-hole arrangement created an anti-kidney vortex while keeping the cooling air covering the wall and distributed laterally. Besides, researches [5,8,12-16] also varied the geometrical and flow parameters on the combined-hole film cooling to observe its impact on the film cooling performances.

In the study of Hassan and Abdullah [14,15], the discussion on the effect of symmetrical compound-angle on the combined-hole film cooling was provided. To further the discussion, the effect of asymmetrical compound-angle on the combined-hole film cooling was covered in the present work. By considering the asymmetrical compound-angle as the main variable, the data and results comparison can be made with the previous study of symmetrical compound-angle. Therefore, the application of asymmetrical compound-angle on the combined-hole film cooling with the change of the distance between two combined-holes in mainstream direction and different blowing ratio will be the main objective of the present work.

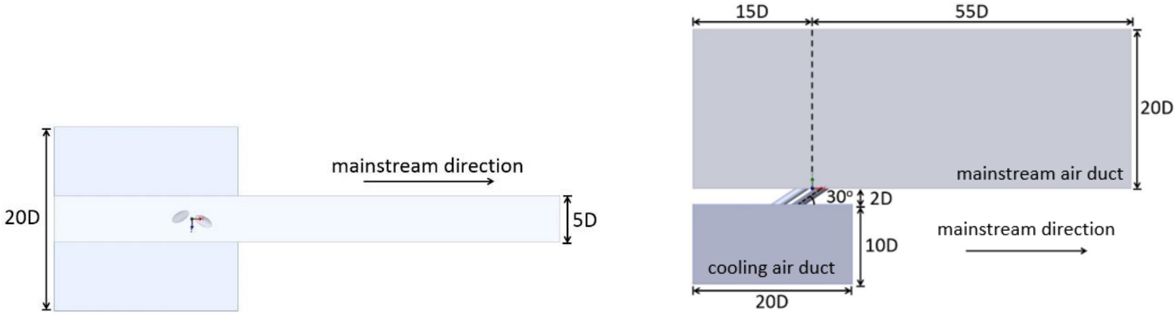
2. Methodology

2.1 Computational Domain

The computational domain in the present work consists of two main sections; mainstream and cooling air duct embedded with combined-hole film cooling. Figure 1 shows the computational domain details from top and side view and Figure 2 (a) shows the details on the hole geometry with considered geometrical configurations. As illustrated, the origin lies in the middle between two centers of combined-hole film cooling. The mainstream direction was set along x-axis and hole diameter, D applied in this work is equal to 3mm. The inclination angle, α was set as 30° in mainstream direction and pitch distance is equal to 5D. The LoD in this work was varied at three different values; 2.5D, 3.0D, 3.5D and asymmetrical compound-angle, γ_1 / γ_2 were varied at -45° / 30° and -60° / 45°. Figure 2 (b) shows the results for mesh dependency test conducted for the case of LoD = 3.0D and γ_1 / γ_2 = -45° / 45° at M = 0.5 with the use of a hybrid mesh with the selected final mesh used approximately 8.2 million nodes for each case.

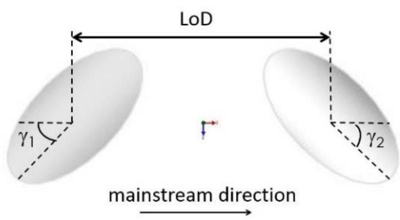
2.2 Numerical Setup

The present work was carried out using ANSYS CFX software involving steady state Reynolds Average Navier Stokes (RANS) analysis with the employment of Shear Stress Transport (SST) turbulence model. The boundary and flow conditions applied in the present work are similar to the work of previous studies [13-15] as shown in Figure 3 and Table 1. The mass flow rate of the cooling air for the combined-hole have been determined with the assumption that both cooling holes are operating at the same blowing ratio and the sum of the required mass flow rate of each hole has been applied at the cooling air inlet of the computational domain.



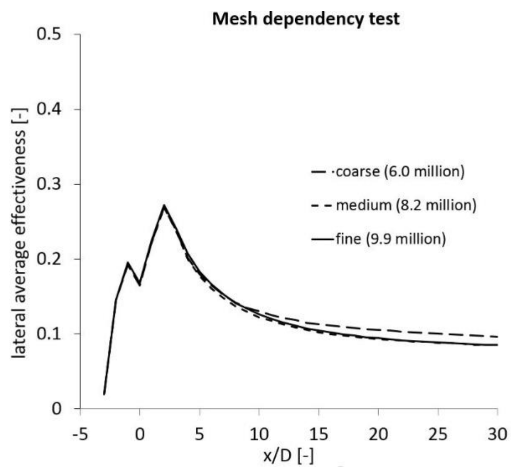
(a) (b)

Fig. 1. Details on computational domain (a) top view; (b) side view



Considered geometrical configurations

LoD	γ1 / γ2	LoD	γ1 / γ2	LoD	γ1 / γ2
2.5	-45° / 30°	3.0	-45° / 30°	3.5	-45° / 30°
	-60° / 45°		-60° / 45°		-60° / 45°



(a) (b)

Fig. 2. (a) Details on hole geometry with considered geometrical configurations; (b) Mesh dependency test

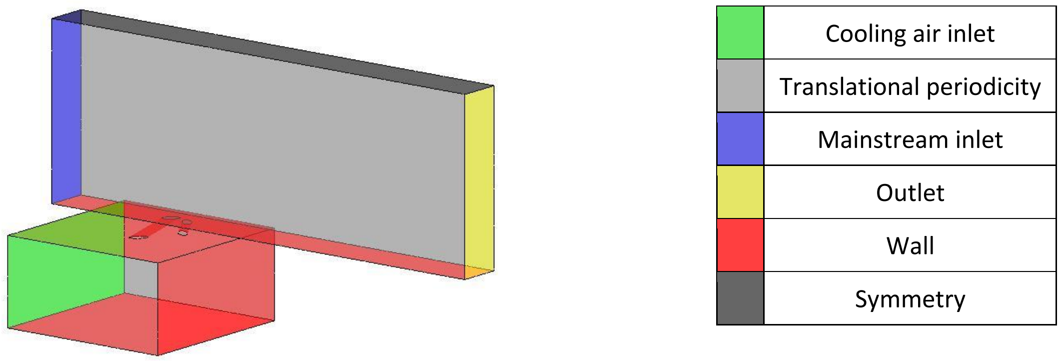


Fig. 3. Boundary conditions

2.3 Validation

The numerical results of combined-hole film cooling effectiveness were validated with the experimental results of previous research reported by Han *et al.*, [13]. Figure 4 shows the comparison of lateral average film cooling effectiveness results for experimental validation. The conditions of both cases were same as LoD = 3.0D and γ_1 / γ_2 = -45° / 45° with M = 0.5. As illustrated, the numerical result of the present work is in agreement with the experimental result at near hole region and further downstream. Based on the lateral average film cooling effectiveness data, the root means square (RMS) error calculated between the present work and experimental results of previous research [13] is ± 4%. Such divergent of the result might be caused by the prediction of the turbulent model on the interaction of the mainstream air and the cooling air which is underestimated. However, better results can be observed at the downstream which is predicted well where the result is more convergence to the experimental results as shown in Figure 4.

Table 1
Flow conditions

Reynold's Number, Re_D	4200
Mainstream Velocity, U_∞	22.065 m/s
Mainstream Temp., T_∞	300 K
Mainstream Turbulent. Intensity, Tu	6%
Blowing Ratio, M	0.5, 1.0, 1.5
Cooling air Inlet Temp., T_c	310 K

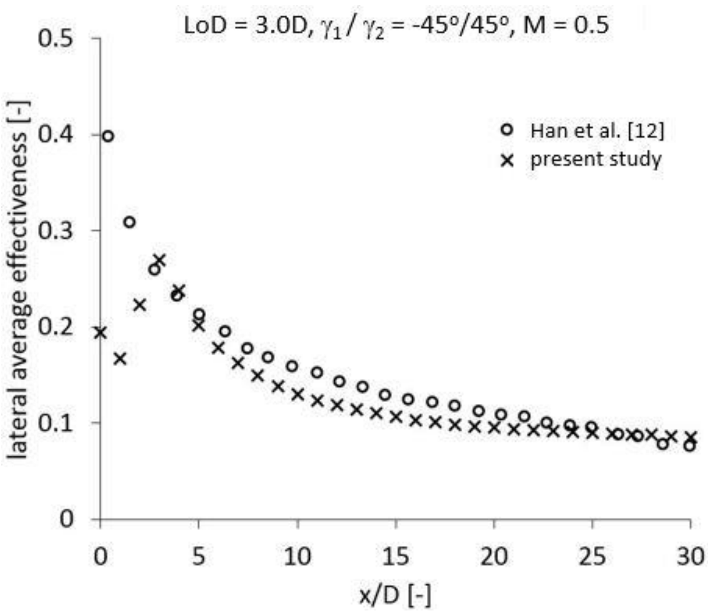


Fig. 4. Experimental validation

2.4 Performance Indicator

The performance of a film cooling system in the present work measured by non-dimensionless temperature as given in Eq. (1) with T_∞, T_{aw} and T_c are mainstream air temperature, adiabatic wall temperature and cooling air temperature respectively. This variable is also generally known as the film cooling effectiveness, *fce* which 0 of film cooling effectiveness indicates very poor cooling air coverage on the wall while 1 of film cooling effectiveness indicates very effective cooling air coverage on the wall.

$$Film\ cooling\ effectiveness, fce = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \tag{1}$$

3. Results

3.1 Film Cooling Effectiveness

Figure 5 shows the film cooling effectiveness distributions for all considered cases at blowing ratio, M = 0.5. It can be observed that increase of LoD from 2.5 to 3.5 in both γ_1 / γ_2 = -45° / 30° and γ_1 / γ_2 = -60° / 45° does not provide significant effect on the film cooling distribution further downstream of the cooling hole. However, slight improvement in terms of film cooling effectiveness can be observes at vicinity of the cooling holes with higher LoD value helps the coolant to remain attach to the surface further downstream. On the other hand, different γ_1 / γ_2 values helps to improve the lateral spread of the coolant which can be observed in terms of lateral average film cooling effectiveness as shown in Figure 6.

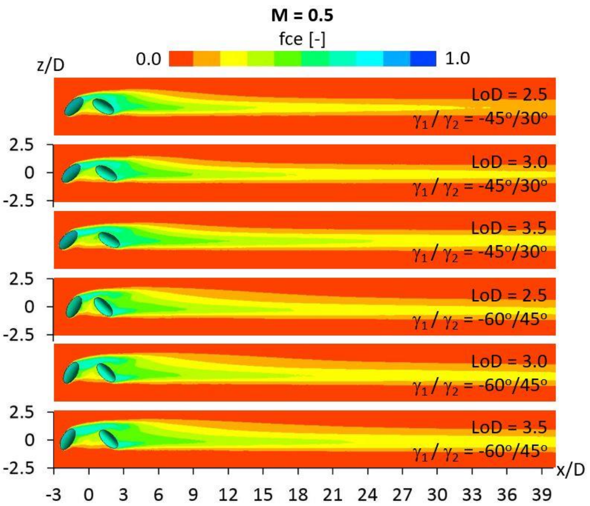


Fig. 5. Film cooling effectiveness distributions at M = 0.5

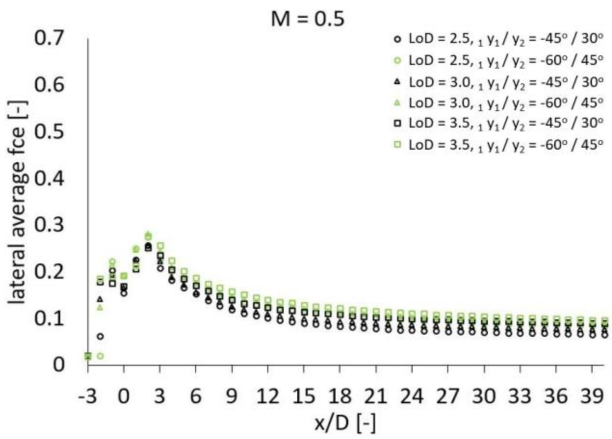


Fig. 6. Lateral average film cooling effectiveness at M = 0.5

In the case of M = 1.0, enhanced lateral coverage of film cooling effectiveness was observed in all cases. As illustrated in Figure 7, better film cooling effectiveness were produced as LoD and γ_1 / γ_2 increase. Based on Figure 8, the configurations of LoD = 3.0 at γ_1 / γ_2 = -45° / 30° and LoD = 2.5 at γ_1 / γ_2 = -60° / 45° capable to maintain the lateral average film cooling effectiveness along the mainstream direction. Besides that, the LoD = 3.5 with γ_1 / γ_2 = -60° / 45° have better film cooling coverage at early downstream in comparison with the other cases. However, the effectiveness cannot be preserved along the mainstream direction and dropped by 0.13 at further downstream.

Increasing the blowing ratio to M = 1.5, the film cooling effectiveness was completely altered compared to the low blowing ratio, M = 0.5. Better film cooling coverage was observed in all cases considered in the present work. Based on Figure 9, the results at the γ_1 / γ_2 = -45° / 30° have different pattern with the results at γ_1 / γ_2 = -60° / 45°. Correlated with the quantitative measured in the Figure 10, the γ_1 / γ_2 = -45° / 30° cases have lower film cooling effectiveness at early downstream in comparison with the γ_1 / γ_2 = -60° / 45° cases. However, the γ_1 / γ_2 = -45° / 30° cases have better performance at further downstream while the γ_1 / γ_2 = -60° / 45° cases have early dissipation and developed low film cooling region further downstream.

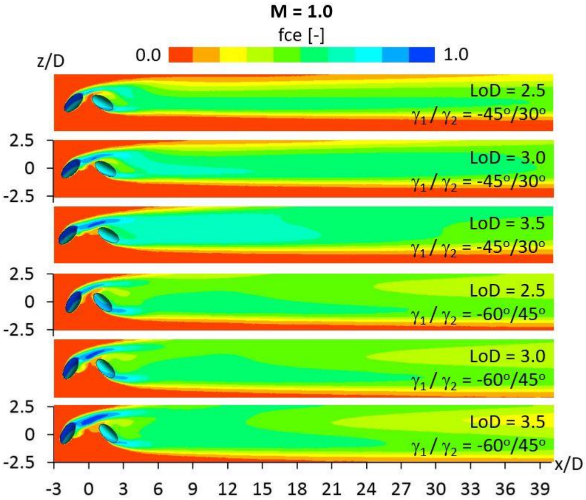


Fig. 7. Film cooling effectiveness distributions at M = 1.0

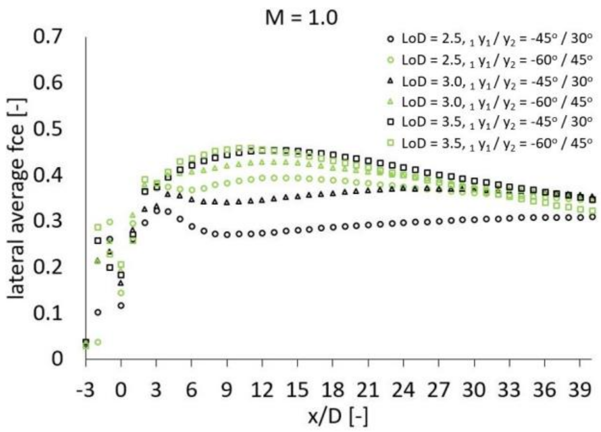


Fig. 8. Lateral average film cooling effectiveness at M = 1.0

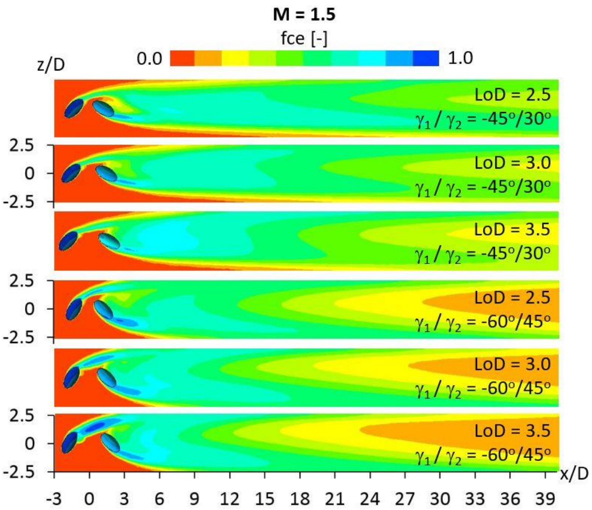


Fig. 9. Film cooling effectiveness distributions at M = 1.5

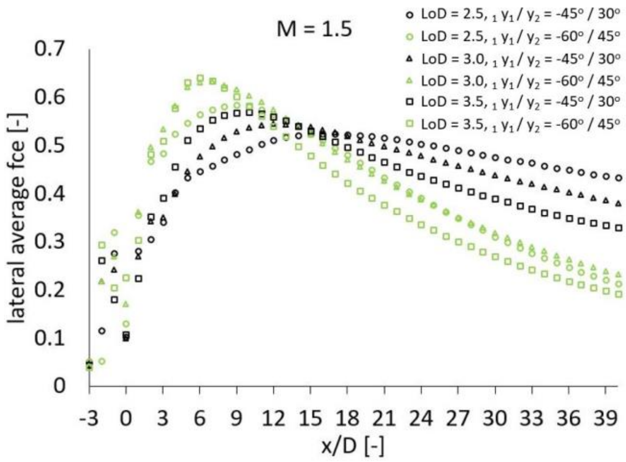


Fig. 10. Lateral average film cooling effectiveness at M = 1.5

Based on the changes of the geometrical parameters; LoD and γ_1 / γ_2, insignificant change of film cooling coverage was observed. Larger LoD applied on the combined-hole film cooling delayed the combination of cooling air from both cooling holes thus move wider in comparison with smaller LoD value. Same as γ_1 / γ_2 applied, larger γ_1 / γ_2 lead the cooling air to expand wider. The cooling air from the upstream hole will move wider and directly penetrate into the mainstream air without entering and combining with the cooling air from the downstream hole thus lateral coverage of film cooling effectiveness was formed.

From the overall observation of film cooling effectiveness, the lateral coverage of film cooling can be observed to increase as the blowing ratio increase. For low blowing ratio, low momentum of cooling air was produced. Therefore, the cooling air ejected will be penetrated into the mainstream air and move in a limited area further downstream thus formed the narrow film cooling coverage. In comparison with the low blowing ratio, high momentum of cooling air was produced in the high blowing ratio cases. Consequently, the cooling air will move wider as it leaves the cooling hole even after emerging with the mainstream air. But, early dissipation of the cooling air further downstream was formed as shown in Figure 9 and the lateral average film cooling effectiveness will decay faster as shown in Figure 10 thus low film cooling effectiveness region was formed further downstream.

3.2 Area Average Film Cooling Effectiveness

Figure 11 presented the results of area average film cooling effectiveness to evaluate the general film cooling effect of different cases. The area considered in these results is the pitch of combined-hole unit, 5D as the width and the length measured from origin to x/D = 40D. At M = 0.5, slight improvement showed as the LoD increase in all cases. However, a huge improvement was observed as the blowing ratio increase to M = 1.0 and M =1.5. At M = 1.0, the area average film cooling effectiveness was increase as the LoD and γ_1 / γ_2 increase. Meanwhile, at M = 1.5, increase the LoD reduces the overall performance at different γ_1 / γ_2 due to cooling air dissipation at further downstream.

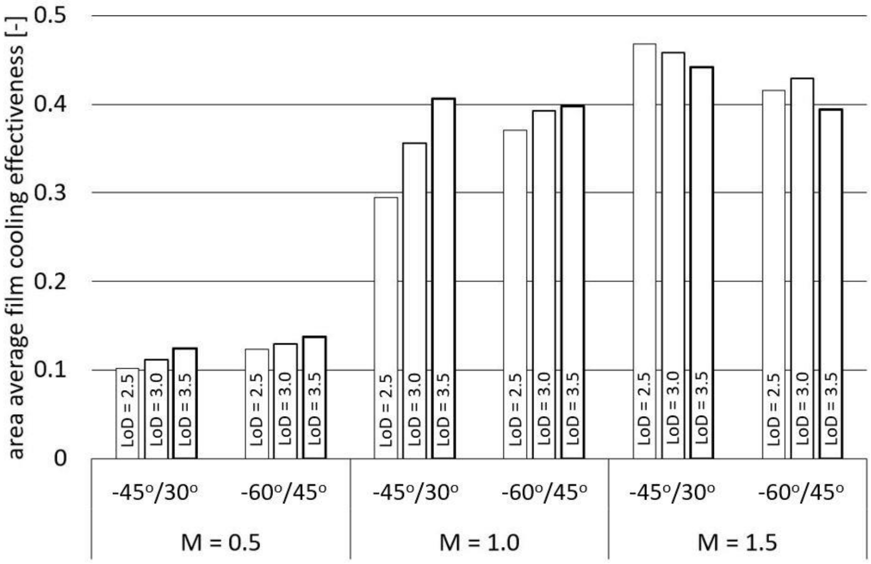


Fig. 11. Area average film cooling effectiveness

4. Conclusions

A batch of simulation focused on the arrangements of combined-hole film cooling system had been carried out using steady state Reynolds Averaged Navier Stokes (RANS) method of ANSYS CFX, with Reynolds number, Re = 4200 at blowing ratios, M = 0.5, 1.0, and 1.5. Six different configurations with combination of different geometrical parameters; γ_1 / γ_2 and LoD have been considered in the present study. The conclusions for present study are as follow

i. Minimal impact was observed as LoD and γ_1 / γ_2 increased.
ii. Significant effect was produced as blowing ratio, M increased.
iii. The optimal arrangement of combined-hole unit were made based on the area average effectiveness bar chart.
iv. At M = 0.5, the arrangement of LoD = 3.5 with γ_1 / γ_2 = -60° / 45° shows better performance.
v. At M = 1.0, the best combination is LoD = 3.5 and γ_1 / γ_2 = -45° / 30°.
vi. At M = 1.5, optimal arrangement of combined-hole is LoD = 2.5 with γ_1 / γ_2 = -45° / 30°.

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References

[1] Goldstein, Richard J. "Film cooling." In *Advances in heat transfer*, vol. 7, pp. 321-379. Elsevier, 1971. https://doi.org/10.1016/S0065-2717(08)70020-0
[2] Goldstein, R. J., E. R. G. Eckert, and F. Burggraf. "Effects of hole geometry and density on three-dimensional film cooling." *International Journal of heat and mass transfer* 17, no. 5 (1974): 595-607. https://doi.org/10.1016/0017-9310(74)90007-6
[3] Thole, K., M. Gritsch, A. Schulz, and S. Wittig. "Flowfield measurements for film-cooling holes with expanded exits." In *ASME 1996 International Gas Turbine and Aeroengine Congress and Exhibition*. American Society of Mechanical Engineers Digital Collection, 1996. https://doi.org/10.1115/96-GT-174
[4] Gritsch, Michael, Achmed Schulz, and Sigmar Wittig. "Film-cooling holes with expanded exits: near-hole heat transfer coefficients." *International Journal of Heat and Fluid Flow* 21, no. 2 (2000): 146-155. https://doi.org/10.1016/S0142-727X(99)00076-4
[5] Han, Chang, and Jing Ren. "Multi-parameter influence on combined-hole film cooling system." *International Journal of Heat and Mass Transfer* 55, no. 15-16 (2012): 4232-4240. https://doi.org/10.1016/j.ijheatmasstransfer.2012.03.064
[6] Kianpour, Ehsan, and Nor Azwadi Che Sidik. "A comparison of cylindrical and row trenched film-cooling holes on a combustor endwall surface at high blowing ratio." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 30, no. 1 (2017): 1-11.
[7] Stratton, Zachary T., and Tom IP Shih. "Effects of Density and Blowing Ratios on the Turbulent Structure and Effectiveness of Film Cooling." *Journal of Turbomachinery* 140, no. 10 (2018). https://doi.org/10.1115/1.4041218
[8] Yao, Jiaxu, Jin Xu, Ke Zhang, Jiang Lei, and Lesley M. Wright. "Effect of Density Ratio on Film-Cooling Effectiveness Distribution and its Uniformity for Several Hole Geometries on a Flat Plate." In *ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*. American Society of Mechanical Engineers Digital Collection, 2018. https://doi.org/10.1115/GT2017-63743
[9] Schmidt, Donald L., Basav Sen, and David G. Bogard. "Film cooling with compound angle holes: adiabatic effectiveness." In *ASME 1994 International Gas Turbine and Aeroengine Congress and Exposition*. American Society of Mechanical Engineers Digital Collection, 1994. https://doi.org/10.1115/94-GT-312
[10] Ligrani, Phillip M., and Joon Sik Lee. "Film cooling from a single row of compound angle holes at high blowing ratios." *International Journal of Rotating Machinery* 2, no. 4 (1996): 259-267. https://doi.org/10.1155/S1023621X96000139
[11] McGovern, K. T., and J. H. Leylek. "A detailed analysis of film cooling physics: Part II—Compound-angle injection with cylindrical holes." *J. Turbomach.* 122, no. 1 (2000): 113-121. https://doi.org/10.1115/1.555434
[12] Kusterer, Karsten, Anas Elyas, Dieter Bohn, Takao Sugimoto, Ryozo Tanaka, and Masahide Kazari. "A parametric study on the influence of the lateral ejection angle of double-jet holes on the film cooling effectiveness for high blowing ratios." In *ASME Turbo Expo 2009: Power for Land, Sea, and Air*, pp. 199-211. American Society of Mechanical Engineers, 2009. https://doi.org/10.1115/GT2009-59321
[13] Han, Chang, Zhongran Chi, Jing Ren, and Hongde Jiang. "Optimal arrangement of combined-hole for improving film cooling effectiveness." *Journal of Thermal Science and Engineering Applications* 7, no. 1 (2015). https://doi.org/10.1115/1.4028976
[14] Hassan, Haswira, and Kamil Abdullah. "Effect of symmetrical compound-angle in combined-hole film cooling." *Journal of Engineering and Applied Sciences*, no. 16 (2016): 9803-9808.
[15] Hassan, Haswira, and Abdullah, Kamil. "Effects of LoD and PoD in combined-hole film cooling." *Journal of Engineering and Applied Sciences,* no. 8 (2017): 2509-2514.
[16] Yao, Jiaxu, Jin Xu, Ke Zhang, Jiang Lei, and Lesley M. Wright. "Interaction of flow and film-cooling effectiveness between double-jet film-cooling holes with various spanwise distances." *Journal of Turbomachinery* 140, no. 12 (2018). https://doi.org/10.1115/1.4041809