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EFFECTS OF LoD AND PoD IN COMBINED-HOLE FILM COOLING

Haswira Hassan and Kamil Abdullah
Center for Energy and Industrial Environmental Studies, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia
E-Mail: mkamil@uthm.edu.my

ABSTRACT

Film cooling technique was used to provide thermal protection for turbine components from the hot combustion gases. Combined-hole film cooling system was introduced as a way to improve the film cooling performances. In the present work, a batch of simulations using combined-hole unit involving two round hole of film cooling with opposite compound-angle were carried out. The aim is to determine the arrangement of combined-hole which will produces highest film cooling effectiveness. The influence of geometrical and flow parameters; distance between two holes in mainstream direction, LoD, distance between two holes in lateral direction, PoD and blowing ratio, M were considered in the present study. The present study had been carried out using steady state Reynolds Averaged Navier Stokes (RANS) analysis of ANSYS CFX, at Reynolds number, Re = 4200 and blowing ratios, M = 0.5, 1.0, and 1.5. Nine different computational models with combination of three different values of PoD and LoD have been considered. The results shows that as the PoD and M increase, the lateral coverage of film cooling also increases, while increase on LoD shows minimal impact on the spread of the coolant downstream of the cooling hole. However, the increase of PoD and M also resulting drastic decrease of film cooling effectiveness downstream of the cooling hole as a result of the lift-off phenomena. Weak interaction between the two jets along the mainstream direction cause separation and lift-off of the coolant at further downstream. In addition to laterally average film cooling effectiveness, the results of area average film cooling effectiveness were also presented to determine the optimal arrangement of combined-hole. Overall, the combined hole film cooling provide better thermal protection in comparison with the single hole configuration.

Keywords: film cooling, double-jet, combined-hole, compound-angle, film cooling effectiveness.

INTRODUCTION

The demand for higher power output and higher thermal efficiency of gas turbines can be achieved through increasing the turbine operating temperature. These high operating temperatures will expose the turbine components particularly the blades to extreme thermal loads which will compromise its durability. Therefore, enhancements of thermal protection on critical surfaces are required to ensure reliability of the turbine components. Film cooling technique was applied on the cooling scheme to provide external protection to the components surface. The compressor bleed air was ejected through small holes on the blade body to provide cover to the blade surface by performing a thin layer of cooled air. The layer will prevent direct contact between the hot gas and the surface while ensuring lower temperature and heat transfer on the turbine components. Distance between cooling holes, shape and angle of cooling holes are example of geometrical conditions influencing the film cooling performances. Different results also can be observed by changing the flow conditions; blowing ratio, density ratio and turbulence intensity.

LITERATURE REVIEW

During the past decades, there are few studies focusing on the flat plate film cooling. Goldstein [1] is one of the earliest researcher whose provide the fundamental understanding of film cooling. Cylindrical hole is a basic and simple film cooling hole, which studied by Gritsch *et al.* [2] to provide film cooling performances of the hole geometries. Han *et al.* [3] also analyzed the film cooling characteristics and mechanism of round-hole film cooling. Goldstein *et al.* [4] studied the effect of angled injection through a discrete hole angled at 35^o and 90^o to the free stream flow direction. Yuen and Martinez-Botas [5] make an experimental study on a cylindrical hole with streamwise angle of 30^o, 60^o and 90^o. The flow pattern produced can be in different forms, depending on the blowing ratio, the cooling gas can remain attached, detach and reattach, or lift off completely. Most of the standard cylindrical hole produced narrow coverage of film cooling effectiveness. Therefore, the idea to change the angle of standard cylindrical hole was introduced. McGovern and Leylek [6] had studied the cylindrical hole with various compound-angle injection. An improved lateral spreading of the cooling gas was formed but, it was turns into one side. The counter-rotating vortex also becomes an asymmetrical with increasing of the compound-angle and fundamentally alters the interaction of the cooling gas and mainstream flow. To overcome the asymmetrical counter-rotating vortex and form anti-kidney vortex, researchers combined two cylindrical hole with opposite compound angle and named as combined-hole or double-jet film cooling hole. Kusterer *et al.* [7] had reported that combined-hole arrangement created an anti-kidney vortex while keep the cooling air covering the wall and distributed laterally. Han *et al.* [8]used the combined-hole arrangement with variation of geometrical parameter, while Kusterer *et al.* [9] varied the flow parameter to simulate the combined-hole film cooling arrangement. Based on both studies, the suited combination between geometrical parameter of combined-hole unit with flow parameter will produce better results and high film cooling performances.

METHODOLOGY

Computational domain

The basic configuration of the simulation consists of two main sections; mainstream and cooling gas duct embedded with combined-hole film cooling. Figure-1 shows details of the computational domain from top and side view. Figure-2 illustrated the details on the hole geometry. Mainstream direction was set along x-axis and the value of D was based on hole diameter, D equal to 3mm. The inclination angle, α was set as 30° in mainstream direction and pitch distance is equal to 5D. LoD and PoD were varied at three different value; 2.5D, 3.0D, 3.5D and 0.0D, 0.5D, 1.0D. The compound-angle of ejection hole, γ_1 / γ_2 were fixed at -45^o / 45^o. As illustrated, the origin lies in the middle between two centers of combined-hole. Figure-3 shows the results for mesh dependency test conducted for the case of PoD = 0.0D, LoD = 3.0D and γ_1 / γ_2= -45^o / 45^o at M = 0.5 with the use of hybrid mesh with the selected final mesh used approximately 8.2 million nodes for each case.

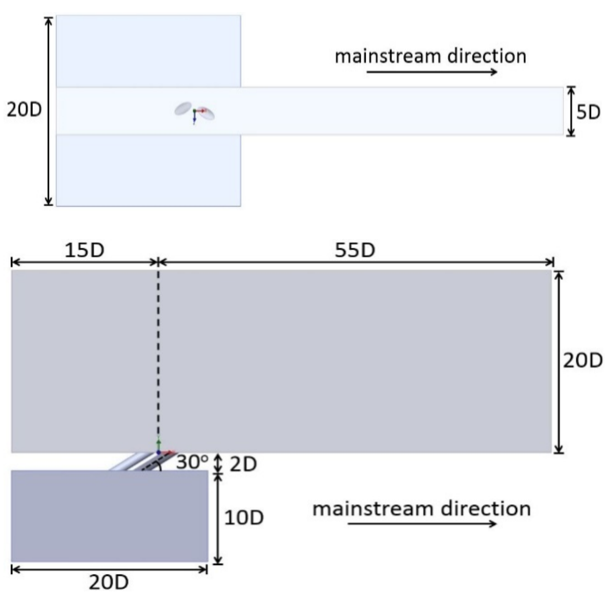

Figure-1. Details on computational domain.

Numerical setup

The present study 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 conditions applied in the present study are similar to the work of Han *et al.* [8] as shown in Table-1. The mass flow rate of the cooling gas for the combined-hole has 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 gas inlet of the computational domain.

LoD	2.5D	3.0D	3.5D
PoD	0.0D	0.5D	1.0D

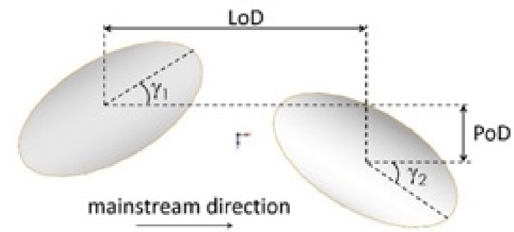

Figure-2. Details on hole geometry.

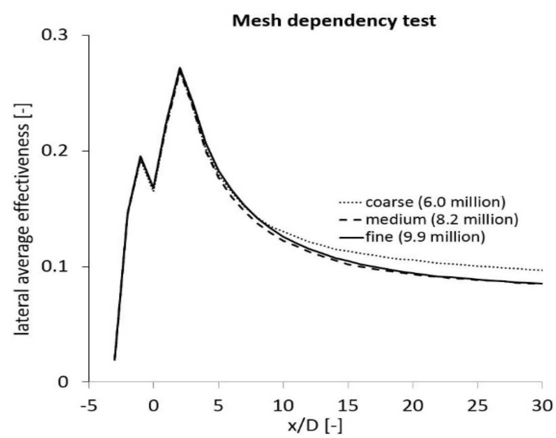

Figure-3. Mesh dependency test.

Table-1. Boundary 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
Secondary Inlet Temp., T_c	310 K

Validation

The numerical results of combined-hole film cooling effectiveness were validated with the experimental results of previous research reported by Han *et al*. [3]. Figure-4 shows the comparison of lateral average effectiveness results for experimental validation. The conditions of both cases were same as PoD = 0.0D, LoD = 3.0D and γ_1 / γ_2 = -45^o/45^o with M = 0.5. The numerical result is in agreement with the experimental result at near hole region and further downstream.

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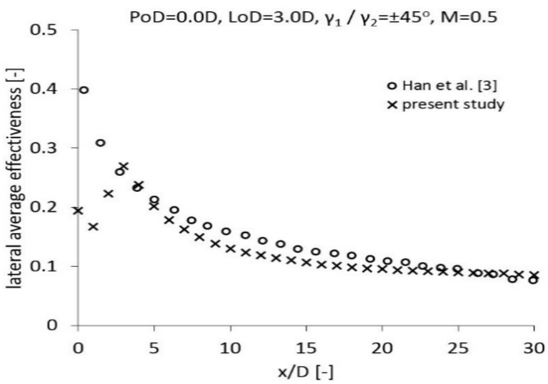

Figure-4. Experimental validation.

RESULTS AND DISCUSSION

Film cooling effectiveness

Figure-5-7 shows the film cooling effectiveness distributions for all considered combined-hole arrangements at different blowing ratios. At low blowing ratio, the lateral coverage of film cooling extends significantly as PoD increases. While increasing LoD shows minimum impact on the spread of the film cooling coverage. At high PoD and blowing ratio, the film cooling effectiveness decay faster and formed large area of low film cooling effectiveness downstream. The phenomena will be discussed in more detail in the later section of this paper.

At low blowing ratio, low penetration of cooling gas and low PoD caused the early mixing between cooling gases ejected from both hole. While high PoD allows the ejected cooling gas from upstream hole to develop with mainstream flow, then mixed with the ejected cooling gas from downstream hole. It cause the cooling gas to cover the wall laterally. The momentum of cooling gas ejected was increased as the blowing ratio increased. Therefore, the cooling gas will dissipate faster and penetrate with the mainstream flow and produce low film cooling effectiveness region at further downstream.

Figure-8-10 shows the lateral average effectiveness at different blowing ratios. In general, the lateral average effectiveness observed to be low at lower blowing ratio. Although the film cooling effectiveness at near hole region increase as the blowing ratio increase, the effectiveness can be observed to decay faster at high blowing ratio further downstream as been discussed earlier in this section. It was supported with lateral average effectiveness which shows same pattern of graph when LoD changed. At M = 1.0, PoD = 0.0D cases show different pattern of film cooling effectiveness distribution. As illustrated in Figure-6, LoD = 3.5D shows high effectiveness at early downstream compare to the others LoD. As illustrated in Figure-9, the same cases of LoD = 3.5D also show reduction of film cooling effectiveness below others LoD at further downstream.

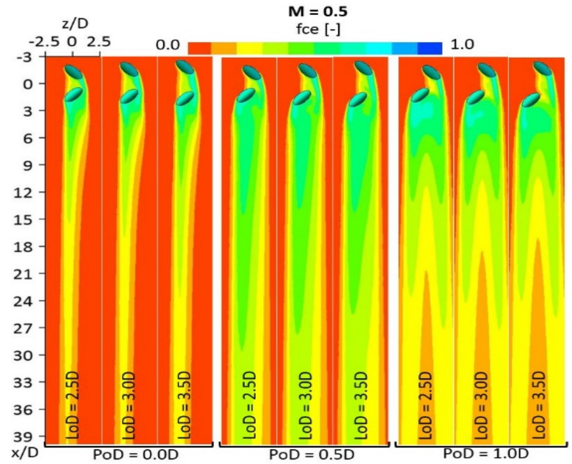

Figure-5. Film cooling effectiveness distributions at M = 0.5.

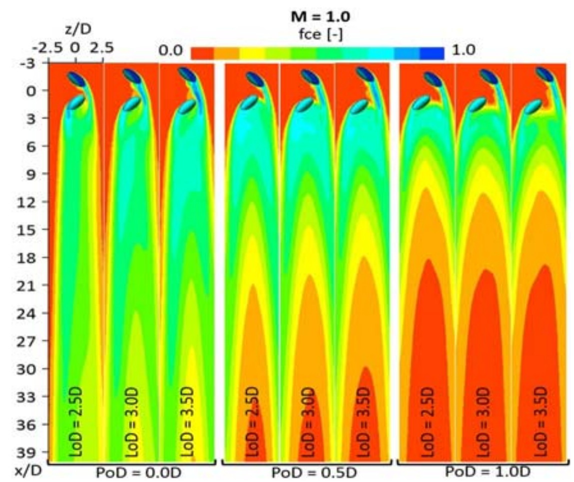

Figure-6. Film cooling effectiveness distributions at M = 1.0.

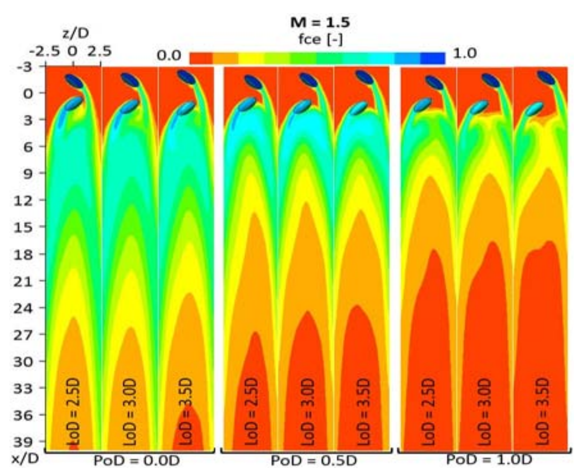

Figure-7. Film cooling effectiveness distributions at M = 1.5.

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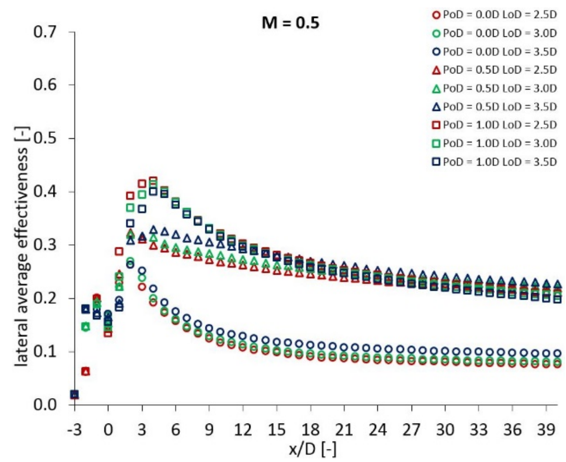

Figure-8. Lateral average effectiveness at M = 0.5.

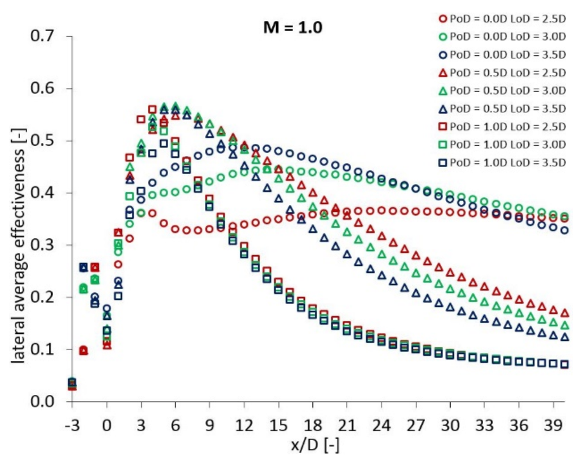

Figure-9. Lateral average effectiveness at M = 1.0.

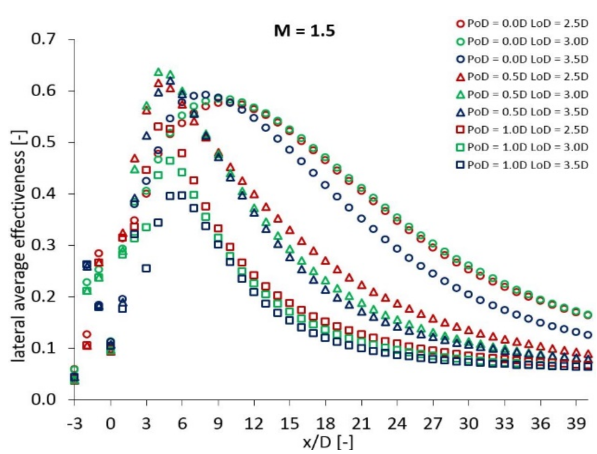

Figure-10. Lateral average effectiveness at M = 1.5.

Lift-off phenomena

Figure-11-13 show the temperature field represented by dimensionless temperature, β on XY plane at x/D = 24 where significant change of flow structure clearly observed. At low blowing ratio, PoD = 0.0D shows narrow result of cooling gas in Figure-5 led to the results of PoD = 0.0Din Figure-11.As PoD increase, the lateral spread of cooling gas also increase. Because of low penetration of cooling gas into the mainstream, lift-off phenomena was not observed at low blowing ratio. At M = 1.0, Figure-6 shows better result as PoD increase but produced low effectiveness region at high PoD. Related with Figure-12, PoD = 1.0D shows complete separation and start to lift-off from covering the bottom surface. Hence, low film cooling effectiveness was produced. When M = 1.5, separation was observed for all PoD arrangements and flow had been lift from covering the wall. From overall observation, higher the blowing ratio will produce higher rate of flow lift-off. Consequently, lower film cooling effectiveness zone will produced between the separated flows at downstream.

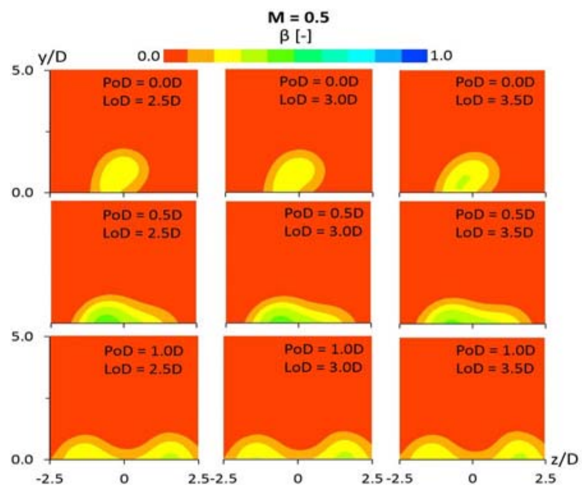

Figure-11. Temperature field at crossing plane x/D = 24, M = 0.5.

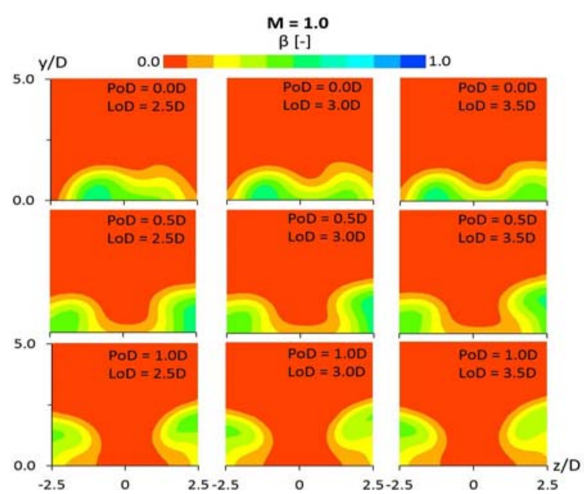

Figure-12. Temperature field at crossing plane x/D = 24, M = 1.0.

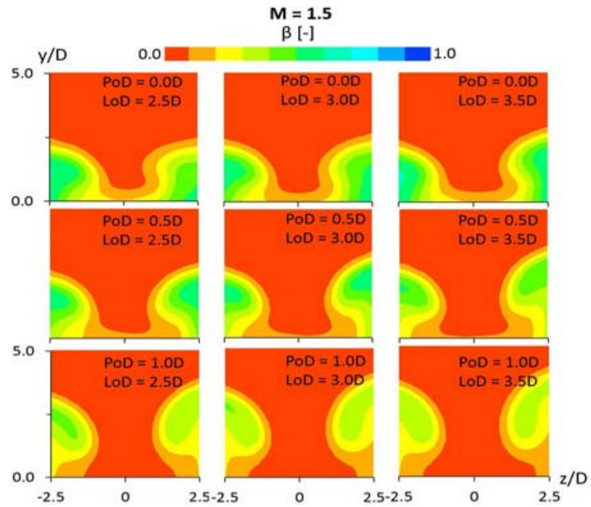

Figure-13. Temperature field at crossing plane x/D = 24, M = 1.5.

In round-hole film cooling system, the kidney vortices which attract hot mainstream gas to the bottom of ejected cooling gas from both sides and lift-off the cooling gas from the wall hindering the film cooling effectiveness. Therefore, combined-hole film cooling system was introduced to produce anti-kidney vortices, which rotate oppositely to kidney vortices. Anti-kidney vortices capable to minimized the lift-off of the ejected cooling gas and enhanced film cooling effectiveness on the wall. Along the mainstream direction, interaction between double ejections of cooling gas become weak and cause the separation and lift-off at further downstream.

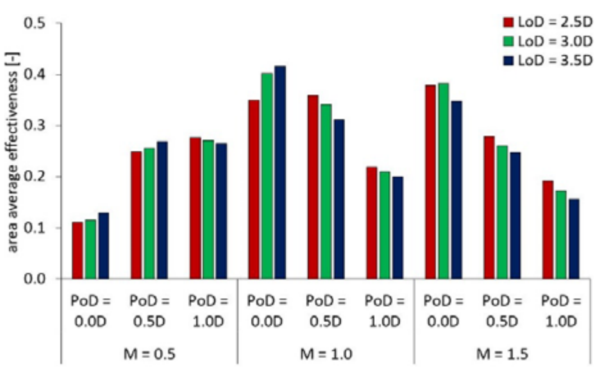

Figure-14. Area average film cooling effectiveness.

Figure-14 illustrates the area average film cooling effectiveness to evaluate the general film cooling effect of different arrangements. The width of the area is pitch of combined-hole unit, 5D and the length is x/D = 40D starting from origin. At low blowing ratio, combination of PoD = 1.0D and LoD = 2.5D have best area average film cooling effectiveness compared to the other arrangements. The other promising arrangements of combined-hole with high film cooling effectiveness were obtained with arrangement of PoD= 0.0D, LoD = 3.5D at M = 1.0, while PoD = 0.0D, LoD = 3.0D at M = 1.5.

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. Nine different computational models with combination of three different values of PoD and LoD have been considered in the present study. The conclusion for present study are as follow:

- The pitch distance, PoDshows significant effect while mainstream distance, LoDshows minimal impact on film cooling performances.
- Increase the blowing ratio will increase the film cooling effectiveness at near hole region but decay drastically at further downstream of the cooling hole.
- Higher the blowing ratio will produce higher rate of flow lift-off hindering the film cooling effectiveness.
- The optimal arrangements of combined-hole unit were selected based on the area average effectiveness with at M = 0.5, the arrangement with PoD = 1.0D and LoD = 2.5D shows the higher area average effectiveness while for M = 1.0 and M = 1.5, the best combination are of PoD = 0.0D, LoD = 3.5Dand PoD = 0.0D, LoD = 2.5D, respectively.

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