VOL. 12, NO. 8, APRIL 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

NUMERICAL INVESTIGATION ON PITCH DISTANCE, COMPOUND ANGLE AND TURBULENCE INTENSITY OFDOUBLE CYLINDRICAL FILM COOLING HOLE GEOMETRY

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ABSTRACT

Film cooling has been extensively used to provide thermal protection for the external surface of the gas turbine blades. Researchers have introduced numerous number of film cooling hole designs and arrangements with aim to reduce the lift-off effect cause by the counter rotating vortex pair (CRVP) produced in the cylindrical cooling hole configuration. Such efforts include the introduction of coupling film cooling designs. The present study focuses on the coupling holes which will later known in this writing as Double Cylindrical Hole (DCH). Two geometrical parameters have been considered; length between holes, PoD and compound angle, β involving nine double cylindrical hole arrangements. In the present work, ANSYS CFX has been used to execute Reynolds Average Navier-Stokes (RANS) analysis with the application of k-ε turbulence model. In general, the results show that the increase in compound angle increases the film cooling effectiveness at the distinct hole region but decays drastically further downstream. Meanwhile, the results of PoD variations demonstrate that larger PoD distance produces higher film cooling effectiveness and also larger area coverage of coolant distribution.

Keywords: film cooling, counter rotating vortex pair, double cylindrical hole, compound angle, effectiveness.

INTRODUCTION

Nowadays, gas turbine has been one of widely used devices in power generation. Modern gas turbine is now operating at very high temperature which exceeds the limits of the components operating temperature. This high temperature will reduce the life span of turbine components, especially the rotor and stator blades. A sophisticated cooling system is required to provide the thermal protection which enables turbine components to operate at this very high temperature which includes film cooling. The film cooling technique is achieved by allowing the coolant to be injected out from the blade surface through cooling holes. The injected coolant will form a thin cool layer preventing direct contact between the hot gases with the blade surface. Most of the available film cooling is discrete hole cylindrical or shaped holes. A lot of researches have been done to improve the performance of the film cooling which is exposed to the Counter Rotating Vortex Pair (CRVP) phenomena thus hindering the film cooling effectiveness downstream of the cooling hole.

Although shaped film cooling hole known to produce better film cooling effectiveness, single hole still has been used extensively due to its high manufacturability. The present research trend shows a lot of efforts have been made on new cooling hole geometry aiming to reduce the effect of CRVP including trenched hole and anti-vortex hole. One of the means to reduce the CRVP effect is by introducing new film cooling hole arrangement namely Double Cylindrical Hole (DCH) film cooling. The present study aims to provide information on the effects of geometrical and flow parameters on the thermal characteristic of the DCH. The study focuses on the effects of two parameters; compound angle, β and the length between holes, PoD.Figure-1 shows variations for the compound angle and the length between the holes considered in the present study. Based on these parameters, nine double cylindrical hole arrangements have been considered as been listed in Figure 1.

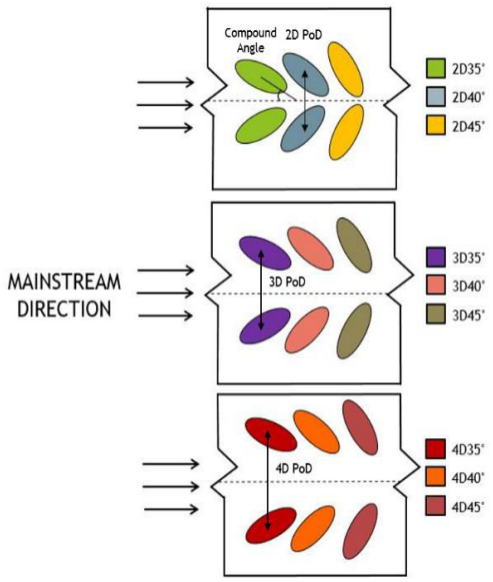

Figure-1. Compound angle and length between holes details.

LITERATURE REVIEW

Film cooling on turbine components has been long studied since the 1970's. Han *et al.* [1] has provided a comprehensive review of film cooling parameters including film hole geometries and flow conditions. The

film cooling protection offered by traditional, round (cylindrical) film cooling holes is strongly affected by the ejection angle of the hole and the coolant to mainstream blowing ratio. Decreasing the injection angle of the hole allows the coolant to remain attached to the surface while minimizing interaction with the mainstream flow. Goldstein *et al.* [2] have considered a new geometrical setup which is a film cooling with the expanded exits. The result shows the momentum of the coolant exiting the hole is reduced when the cross sectional area at exit hole is increased. As the coolant velocity decreases, the coolant remains attached to the surface even at elevated blowing ratios. The observation was later confirmed by Gritsch *et al.* [3]. The results show that the hole with expanded exits have profoundly lower heat transfer coefficient at elevated blowing ratios compared to a cylindrical hole. Moreover the laidback fan shaped hole provides better lateral spreading of the jet as compared to the fan shaped hole and therefore, lower laterally averaged heat transfer coefficient. Islami *et al.* [4] have proposed a new configuration of film cooling known as trenched hole. This study presents a comparative-numerical investigation of film cooling from a row of simple and compound-angle holes injected at 35° on a flat plate with four film cooling configurations: (1) cylindrical film hole; (2) 15° forward diffused film hole; (3) trenched cylindrical film hole; (4) trenched 15° forward-diffused film hole. The result shows that the film cooling effectiveness by trenched shaped holes is higher than all other configurations both in spanwise and streamwise especially downstream of the injection. Years after that, advanced film cooling was introduced. To overcome the effect of the CRVP, Heidmann *et al.* [5] have proposed an anti-vortex cooling hole design. The anti-vortex cooling hole consists of single hole which accompany with two sister hole. Using this new geometry, it is shown that there is an improvement in terms of the film cooling effectiveness compared to the single cylindrical hole at the same value blowing ratio. It is proved that it can reduce the secondary flow field effects better than before and it is also confirmed by Schulz *et al.* [6]. Wright *et al.* [7] have introduced a double cylindrical film cooling configuration as an alternative to traditional cylindrical and fanshaped, laidback holes. This experimental investigation utilizes a Stereo-Particle Image Velocimetry (S-PIV) to quantitatively assess the ability of the proposed design to weaken or mitigate the counter-rotating vortices formed within the jet structure. The three-dimensional flow field measurements are combined with surface film cooling effectiveness measurements obtained using Pressure Sensitive Paint (PSP). The double cylindrical hole geometry consists of two compound angle holes. The inclination of each hole is $\theta = 35°$, and the compound angle of the holes is $\beta = \pm 45°$ (with the holes angled toward one another). The simple angle cylindrical and shaped holes both have an inclination angle of $\theta = 35°$. The result finds that the double cylindrical holes film cooling improves the film cooling effectiveness at the exit hole but following the single cylindrical hole pattern as it move further downstream. It is believed that this arrangement still not in full potential with length between the cooling hole and compound angle variation could significantly improve the film cooling effectiveness.

METHODOLOGY

The present study aims to investigate the effects of double cylindrical hole configurations on the film cooling effectiveness involving nine geometrical arrangements based on the compound angles and length between holes variation.

Computational domains

Figure-2 shows the computational domains that been used for all cases. The general computational domain consists of the two symmetrical holes inclined at $\theta = 35^{\circ}$ towards the mainstream direction. In order to ensure the accuracy of the numerical procedure, the mesh dependency test has been carried out prior to the analysis. Three mesh setups have been considered according to the number of nodes. Figure-3 shows the result for the mesh dependency test and the mesh setup of 7 million nodes has been choose for the present analysis.

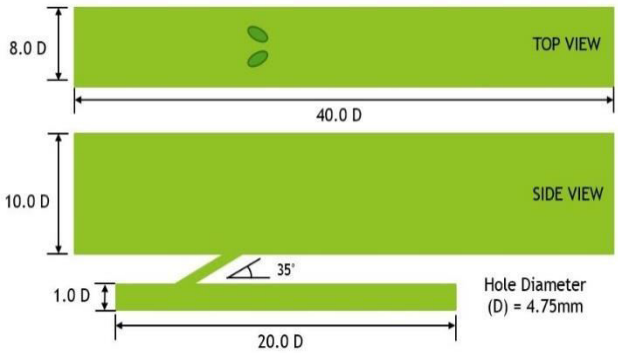

Figure-2. Computational domain details.

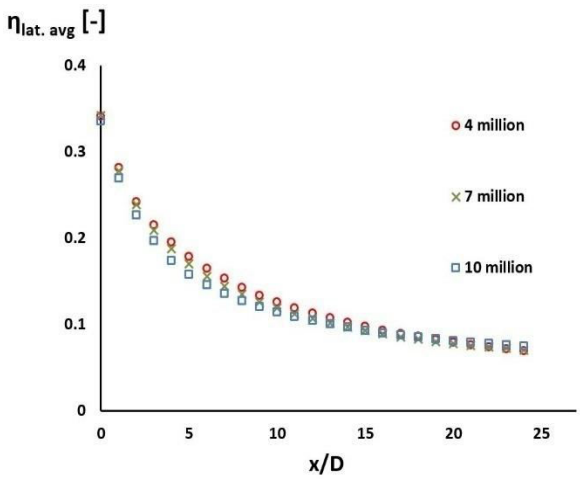

Figure-3. Mesh dependency test result.

VOL. 12, NO. 8, APRIL 2017 ISSN 1819-6608
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Table-1. Boundary condition details.

Blowing ratio, M	0.5, 1.0, 1.5
Density ratio, DR	1.1
Turbulence intensity, Tu	1%, 5%, 10%
Mainstream temperature, T_∞	297 K
Mainstream velocity, V_∞	10 m/s
Reynolds number, Re	11000

Numerical setup

ANSYS CFX software was used in the present numerical investigation. Steady state Reynolds Average Navier Stoke analysis has been applied coupled with the k-ε turbulence model. Table-1 shows the boundary conditions details. Boundary conditions applied in the present study have been referred to Schulz *et al*. [6] and Wright *et al*. [7] with the secondary mass flow rate has been determined by assuming that both cylindrical holes have the same blowing ratio.

Benchmarking

The present numerical investigation is validated with the experimental results available in the literature for single cylindrical hole at blowing ratio, M = 1.5. Figure-4 shows the comparison between the present result and the result of Wright *et al*. [7]. The present result shows a good agreement with the experimental results starting from x/D = 7 onward. However, slight difference can be observed between the laterally average film of the present study and the experimental result at the range of ±4%. The difference might be due to the incapability of the model to capture the complex vortex structure occurred at the region.

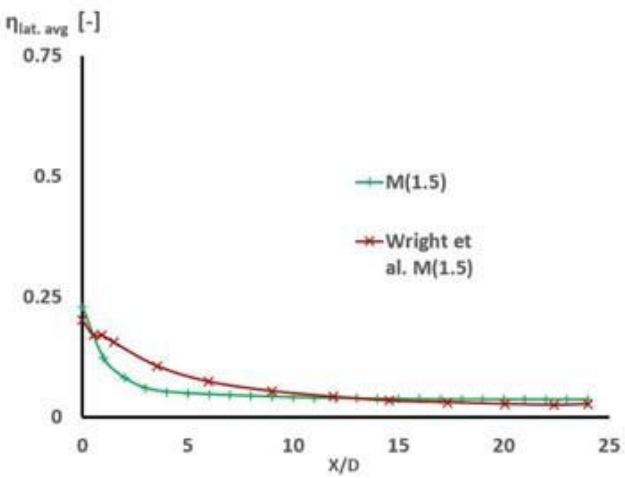

Figure-4. Comparison between present numerical and previous experimental.

RESULTS AND DISCUSSIONS

Effects of blowing ratio and turbulence intensity

In the present study, three blowing ratios have been considered; 0.5, 1.0 and 1.5 and for the turbulence intensity, three values that have been considered; 1%, 5% and 10%. Figure-5 illustrates the comparison of the blowing ratios and turbulence intensities to the film cooling distribution on baseline arrangement. Focusing on the blowing ratio, the result shows a distinct pattern of distribution where as the blowing ratio is increasing, the area of distribution decreases. This finding provides the evidence for the general ideas of the effect of blowing ratio towards the effectiveness. On the other hand, the effects of the turbulence intensities show that the higher turbulence intensity produces higher effectiveness although it's only had a minimal impact present in all cases. This effect is due to the turbulent mixing reduces the penetration of the coolant into the mainstream. Figure-6 demonstrate the effects on increased turbulence intensity from Tu≈1% until Tu≈10% on the dimensionless temperature, γ field at location x/D=3 using DCH 2D45 with blowing ratio, M = 0.5. The result shows clearly that the higher intensity produces almost same coolant coverage compared to the lower intensity. Based on the result, for case 2D45, the best parameter for effectiveness is blowing ratio, M=0.5 and turbulence intensity, Tu = 10%. Figure-7 proved the previous statement.

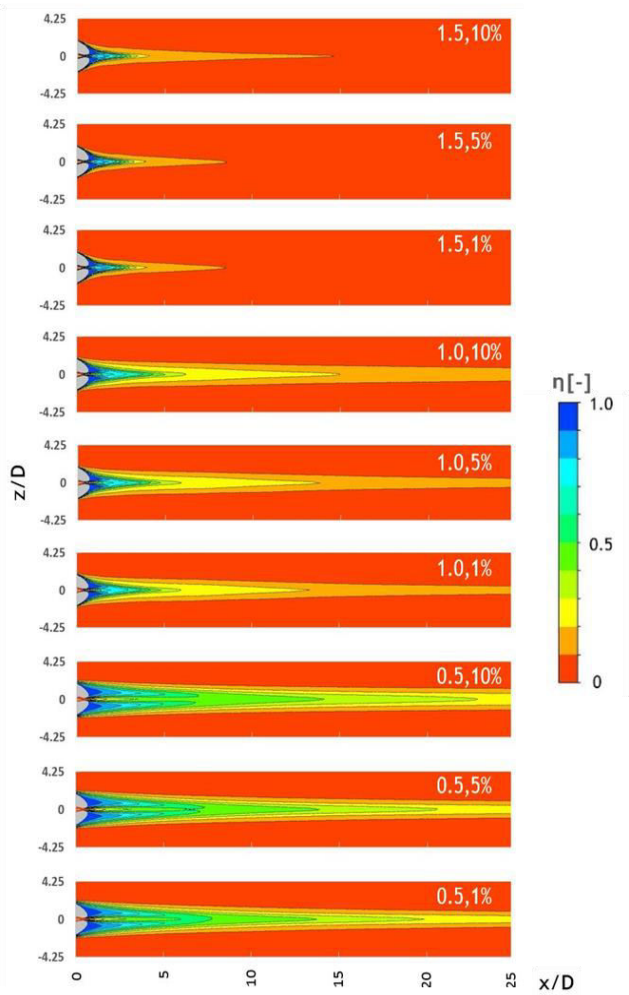

Figure-5. Blowing ratio and turbulence intensity comparison.

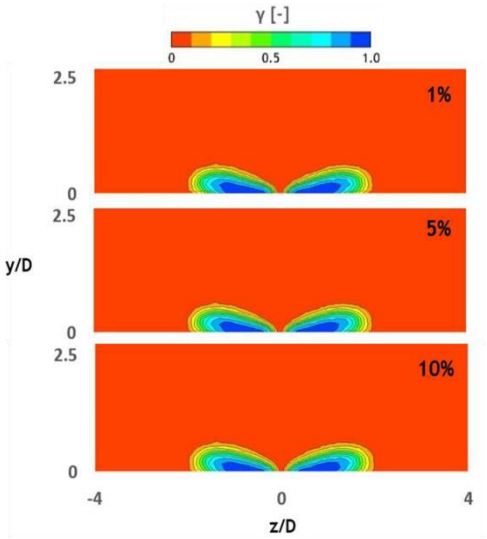

Figure-6. Temperature field for Tu = 1%, 5% and 10% at x/D=3 for DCH 2D45.

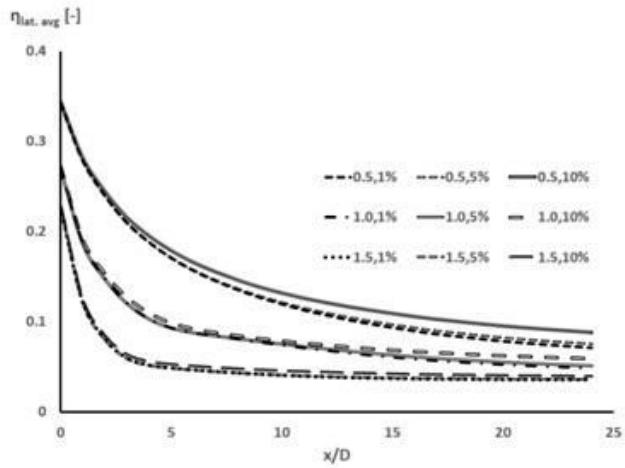

Figure-7. Laterally average film cooling effectiveness for 2D45.

Compound angle and PoD.

Figure-8 demonstrates the results for the film cooling effectiveness distribution contour for all cases for blowing ratio, M = 0.5. All figures are shown in z/D vs x/D axis.

The result shows the comparison of compound angles and PoD. As for the comparison for compound angles, the higher compound angle, 45˚ is producing high peak point of effectiveness at the near hole region. However, the effectiveness decays faster compared to the other compound angle further the downstream even though the difference is minimal. This due to the jets from both hole meets earlier and combined into a single jet. As it combined the momentum of the jet is increasing thus it tends to lift off from the wall surface. Meanwhile, for comparison of Pod, the result indicates that the higher PoD higher film cooling effectiveness. The reason is still same as before as the length between hole is more further, the points of jets meet become more further the downstream. In terms of coverage, the higher PoD also covers larger area distribution compared to the others. Figure-9 shows the lateral average film cooling effectiveness plotted for all cases. From the figure, it shows clearly that the cases with higher PoD dominate the other cases in term of effectiveness. Comparing to the Wright *et al* [7] findings, the present study shows improvement in term of effectiveness.

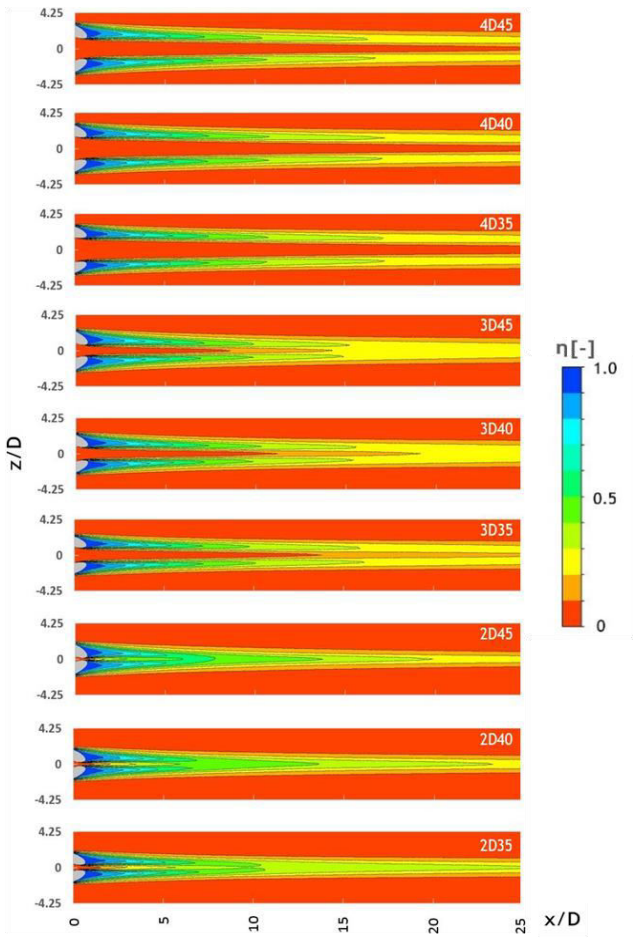

Figure-8. Film cooling distribution for all cases.

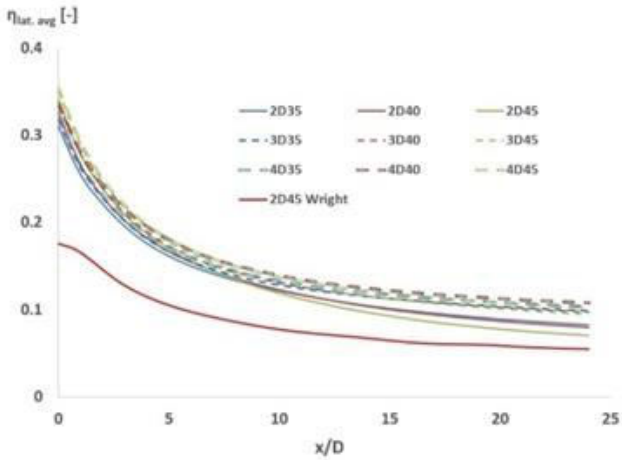

Figure-9. Laterally average film cooling effectiveness for all cases.

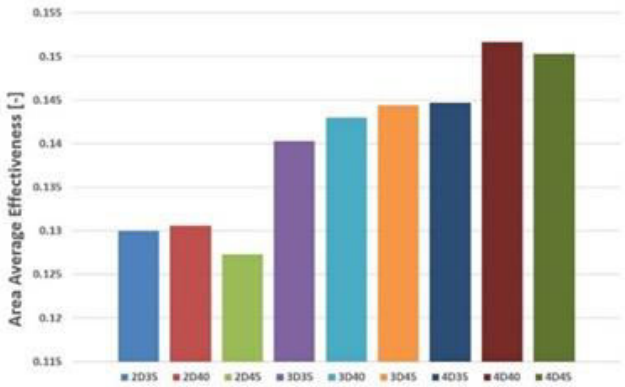

Figure-10. Area average film cooling effectiveness for all cases.

Area average film cooling effectiveness

Area average effectiveness is introduced to evaluate the general film cooling effect on the different arrangement. The size of the region that have been applied is 25D downstream of cooling holes and 8D on the z-direction. The area average effectiveness of all cases for M=0.5 are illustrated in Figure-10.As illustrated in Figure 10, the pattern for each PoD is different. For 2D PoD cases, the highest area average effectiveness was produced by 2D40 followed by 2D35 and 2D45. Meanwhile, for PoD = 3D, the pattern shows that the higher the compound angle, the higher the area average effectiveness. Lastly, for PoD = 4D, the pattern is almost same as 2D where 40˚ producing the highest effectiveness but the lowest is the 35 ˚. In comparison for all cases, the area average effectiveness is dominated by PoD = 4D where 4D45 case is producing the highest effectiveness in term of area averaged.

Flow field phenomena

In flow field phenomena studies, the case that has been studied is the comparison of the effects of different blowing ratios. Figure 10 shows the vorticity contour plot comparison for 2D45 case at distinct location, x/D = 5 using a different blowing ratio.Figure-11 demonstrates the pattern of vorticity as the blowing ratio is increasing. As the blowing ratio increasing, the vortices become stronger and the magnitude become larger. By increasing the blowing ratio, the mixing between the coolant and the mainstream become more intense which it leads to the stronger formation of vortex. Besides the formation of vortices, the result also shows information on one more phenomena that known as lift off phenomena. When the hot gases from the mainstream meets the coolant, the vortices formed and these vortices will accommodate the space underneath the coolant jet thus heat up the blade surface. As this happens, the coolant jet eventually tends to leave from attaching to the blade's surface thus at that point, film cooling effectiveness starts decreases. The phenomena can be seen as the magnitude of the vortex is increasing from x/D ≈0.5 at M = 0.5 and as for the M = 1.5, the vortex's magnitude is x/D ≈ 1.25.

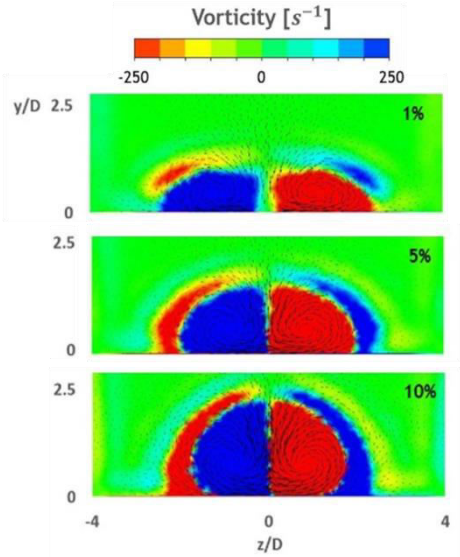

Figure-11. Vorticity counter plot for 2D45; x/D=5.

CONCLUSIONS

The present study involved a numerical investigation of a double cylindrical hole film cooling geometries. ANSYS CFX is used for the numerical investigation with the simulation of RANS – Reynolds Averaged Navier Stokes is involving the blowing ratio, M = 0.5,1.0, 1.5, turbulence model, Tu = 1%, 5%, 10%, Reynolds number Re = 11000 and also there are nine different cases that have been considered; 2D35, 2D40, 2D45, 3D35, 3D40, 3D45, 4D35, 4D40 and 4D45. The conclusions of the present study are as follows:

- All new proposed double cylindrical hole geometry shows improvement compared to the baseline design.
- In comparison for all cases, case 4D40 shows the best lateral average and area average effectiveness.
- The effects of the blowing ratio are still following the general ideas where the higher blowing ratio, the lower the film cooling effectiveness
- For turbulence intensity, the effects on the film cooling effectiveness is minimal, but still higher intensity produce better effectiveness.
- In flow field phenomena, the magnitude of vortices is becoming stronger and bigger by increasing the blowing ratio, thus the coolant jet tends to lift off and film cooling effectiveness starts to decrease.

ACKNOWLEDGEMENTS

The authors would like to thank both Universiti Tun Hussien Onn Malaysia (UTHM) and Ministry of Education Malaysia (MoE) for the financial support through Research Acculturation Grant Scheme (R036).

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