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# NUMERICAL INVESTIGATION OF PLACING AN UPSTREAM RAMPS IN DOUBLE CYLINDRICAL HOLE FILM COOLING

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**ABSTRACT**

In order to provide thermal protection for the external surface of the gas turbine blades, film cooling technique has been applied. With the aim to reduce the lift-off effect cause by the counter rotating vortex pair (CRVP) formed in the cylindrical cooling hole configuration, coupling film cooling designs have been introduced. Double Cylindrical Hole (DCH) which is one of the coupling holes is the main subject for the present study with the implementation of two geometrical parameters; length between the holes in x-direction, LoD and upstream ramp. Five double cylindrical hole arrangements have been developed with these two parameters and DCH 2D35 is considered as the baseline which will be discuss more later on. Meanwhile for the flow parameter, the main parameter considered is blowing ratio, M. ANSYS CFX ver. 15 has been used in the present work and all the analyses have been carried out using Reynolds Average Navier Stokes analysis with the implementation of k-ε turbulence model. In general, the results show that the increase in LoD hindering the film cooling effectiveness at the distinct hole region, but decays slower in the downstream compared to the baseline design. Meanwhile, the results of upstream ramp variations demonstrate that the upstream ramp shows significant improvement of film cooling effectiveness at near exit hole region, but as the film cooling moves further downstream, it decays rapidly in comparison with the baseline. As for the blowing ratio effect, the film cooling have been observe to decay as the blowing ratio increases similar to the general ideas of conventional cooling hole.

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

## INTRODUCTION

Gas turbine is one of the important device in this modern era which widely used in power generation and transportation. It is used to convert the high pressure and high temperature combustion air from the combustion chamber to mechanical energy through the turbine. High turbine inlet temperature is necessary to provide more available energy to be converted by the turbine. In order to increase the efficiencies of gas turbine, very high temperature inlet is required which usually exceeds the thermal limitation of the turbine components. Such condition, will affects the durability of turbine components especially stator and rotor blade. In order to reduce such effects, a sophisticated cooling system is required to provide the thermal protection which includes film cooling technique. Film cooling technique is achieved by allowing the coolant to be injected out from the blade surface through cooling holes. A thin cool layer will be formed from the injected coolant preventing direct contact between the hot gas and blade surface thus reducing the surface temperature of the component. Most of the available film cooling is a discrete cylindrical hole or shaped holes. As the research to improve the performances of film cooling continues, researchers found out that discrete cylindrical hole will produce a dominant flow structure known as Counter Rotating Vortex Pair (CRVP), which hindering the film cooling effectiveness. 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 effects is by introducing new film cooling hole arrangement with the implementation of upstream ramp on film cooling. The present study aims to provide information on the effects of geometrical and flow parameters on the thermal characteristic of the modified DCH instead changing the shaped of the holes. Two geometrical parameters are being focused on; the length between the holes in x direction, LoD and the upstream ramp. Meanwhile for flow parameters, blowing ratio have been considered as the main flow parameter for the present study. Figure-1 shows the details of the film cooling holes.

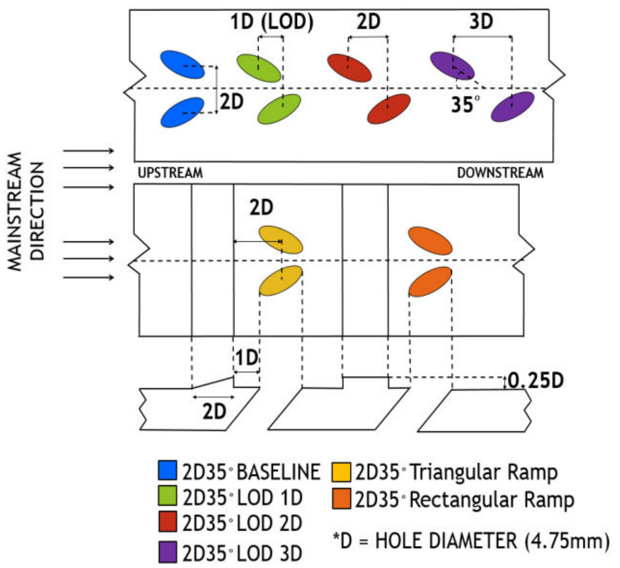


**Figure-1.** LoD and upstream ramp details.

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**LITERATURE REVIEW**

Film cooling of turbine components has been long studied since the 1970's, with numerous studies which focusing on the effects of the film cooling performances. Bergeles *et al.* [1] have discovered formation of vortices as the coolant and the mainstream mixed which is known as Counter Rotating Vortex Pair (CRVP). These vortices are degrading the film cooling effectiveness and leads to lift-off of the jets from the blade surface. As to prevent the jets leaving the surface due to the lift-off effect, researchers have put their interest on the shaped exit holes. In the early work, Goldstein *et al.* [2] were proposing a new geometrical setup which known as expanded exits film cooling. The result demonstrates that the momentum of the coolant leaving the hole is decreased when the cross sectional area at exit hole is increased. It can be conclude that when the coolant velocity decreases while using the expanded exit hole, the coolant remains attached to the surface even at elevated blowing ratios. The observation was later confirmed by Gritsch *et al.* [3] with additional findings 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. Han *et al.* [4] has produced a comprehensive review of film cooling parameters for film hole geometry and flow conditions. The review highlights that the film cooling protection given by traditional, round (cylindrical) film cooling holes is strongly affected by the coolant to mainstream blowing ratio and ejection angle of the hole. Decreasing the injection angle of the hole allows the coolant to remain attached to the surface while minimizing interaction with the mainstream flow. Years after that, more complicated film cooling configuration was introduced. To overcome the effect of the CRVP, Heidmann *et al.* [5] have proposed a new film cooling design which is an anti-vortex cooling hole design. The anti-vortex cooling hole consists of single hole which accompany with two sister hole. The result shows that there is an improvement in film cooling effectiveness compared to the traditional single cylindrical hole while using the exact amount of coolant 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]. As an alternative to conventional cylindrical and fan shaped, laidback holes, Wright *et al.* [7] have introduced a double cylindrical film cooling configuration. 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). This experimental investigation utilizes a Stereo-Particle Image Velocimetry (S-PIV) to quantitatively assess the ability of the proposed design, double cylindrical hole geometry 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 simple angle cylindrical and shaped holes both have an inclination angle of $\theta = 35°$. The results show that double cylindrical holes film cooling improves the film cooling effectiveness at the exit hole but as it move further downstream, it start to produced similar pattern as the single cylindrical hole. It is believed that this arrangement still not in full potential. Besides changing the geometry of the exit holes, additional flow devices could also help to improve the propose cooling hole configuration. Na and Shih [8] have tested the cooling hole with the implementation of upstream ramp which expected to modify the approaching boundary layer flow structure and the interaction between mainstream and coolant. The results show promising increase in term of film cooling distribution and also lateral film cooling effectiveness. This result also has been confirmed by Samad and Halder [9] later on in their work. The effects of the upstream ramp have also been studied by Barigozzi *et al* [10] which being applied to cylindrical and fan-shaped film cooling. The result shows a good improvement in terms of film cooling effectiveness for the cylindrical hole and vice versa or the shaped hole.

**METHODOLOGY**

**Computational domains**

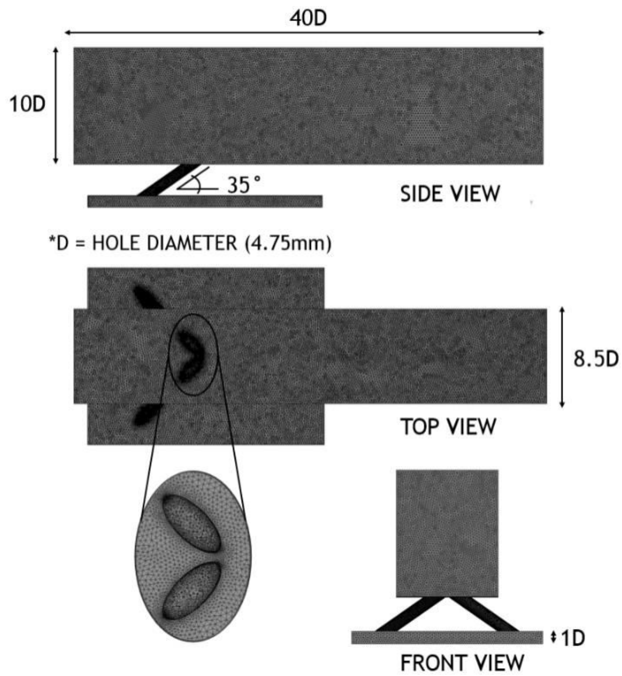


**Figure-2.** Computational domain details with mesh.

The focus of the present study is investigate the effects of double cylindrical hole configurations on the film cooling effectiveness involving five geometrical arrangements based on the length between the holes, LoD and upstream ramp. On top of the aforementioned cases, 2D35 (distance between two holes in z-direction, 2D and compound angle of the holes, 35°) geometry has been assigned as the baseline which the diameter, D is 4.75mm. Meanwhile as for the cases of upstream ramp (Triangular and Rectangular), the height is 0.25D and 2D length whereby the location is 1D before the exit hole as shown in Figure-1. Figure-2 shows the computational domains that been used for all cases. The general computational domain consists of the two symmetrical holes inclined at θ = 35° 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 and 7 million mesh was choose for the present study. Meanwhile for the inflation, , it has been set to satisfy the y+ value equal to 1 with the first layer thickness at 0.01mm.

**Numerical setup**

ANSYS CFX software was used in the present numerical investigation. Steady state Reynolds Average Navier Stoke analysis has been applied using the k-ε turbulence model. Flow conditions applied in the present study have been referred to Schulz *et al.* [6] and Wright *et al.* [7]. Table-1 shows the flow conditions details with secondary mass flow rate has been determined by assuming that both cylindrical holes have the same blowing ratio. Meanwhile Figure-3 shows the boundary condition details.

**Table-1.** Flow condition details.

| | |
|---|---|
| Blowing ratio, M | 0.5, 1.0, 1.5 |
| Density ratio, DR | 1.1 |
| Mainstream temperature, $T_\infty$ | 297 K |
| Mainstream velocity, $V_\infty$ | 10 m/s |
| Reynolds number, Re | 6000 |

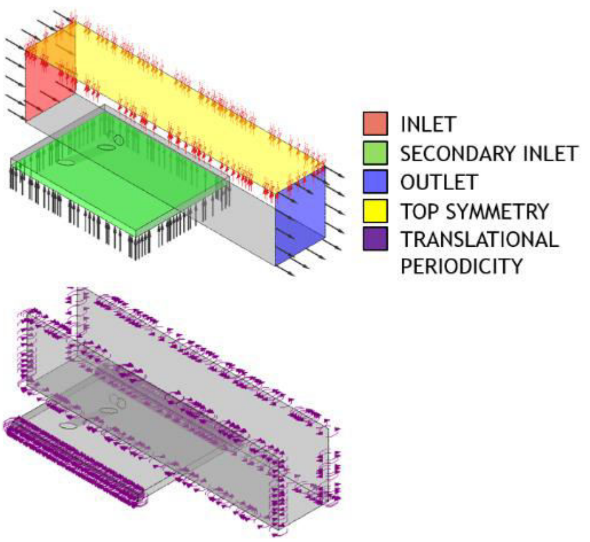


**Figure-3.** Boundary conditions detail.

**Performances indicator**

In film cooling studies, there is one parameter that usually used to find the film cooling performance which is the adiabatic film cooling effectiveness. This dimensionless parameter is defined as

$$\eta_{aw} = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \quad (1)$$

$\eta_{aw}$ = Adiabatic film cooling effectiveness
$T_\infty$ = Mainstream temperature
$T_{aw}$ = Surface temperature
$T_c$ = Coolant temperature

**RESULT AND DISCUSSION**

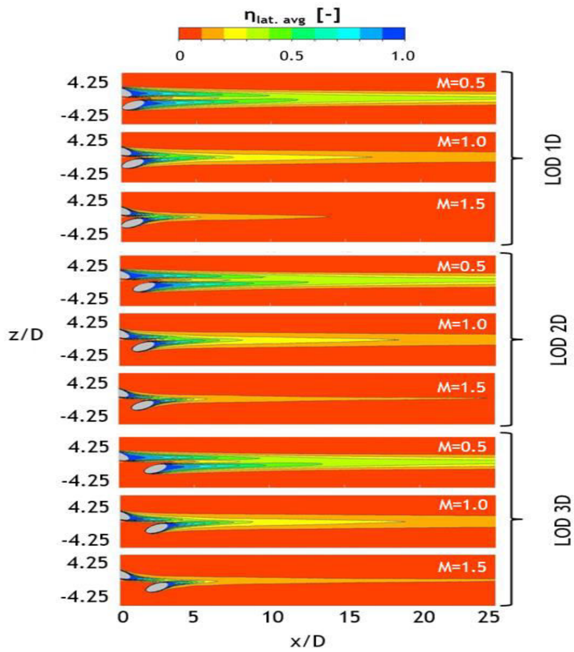


**Figure 4:** Effect of blowing ratio on film cooling distribution for 2D35 LoD 1D, LoD 2D and LoD 3D.

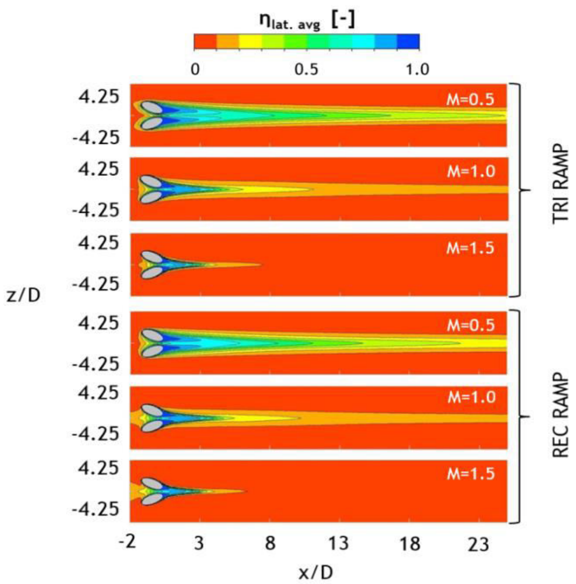


**Figure-5.** Effect of blowing ratio on film cooling distribution for 2D35 tri ramp.

**Blowing ratio effects on film cooling effectiveness**

Focusing on the blowing ratio, the result shows a distinct pattern of distribution whereas the blowing ratio is increasing, the area of distribution decreases and narrowing further the downstream. This is due to the lift off phenomenon which will be discussed later on. On the other hand these finding provides the evidence for the general ideas of the effect of blowing ratio towards the effectiveness where it is apply to all cases. Figure-4 and Figure-5 shows the effect of blowing ratio to the film cooling distribution contour for all cases.

**Length between holes (LoD)**

In the present study, three cooling hole configurations based on LoD have been considered; 1D, 2D and 3D. Figure-6 illustrates the film cooling distribution of LoD in comparison with baseline arrangement for M=0.5.

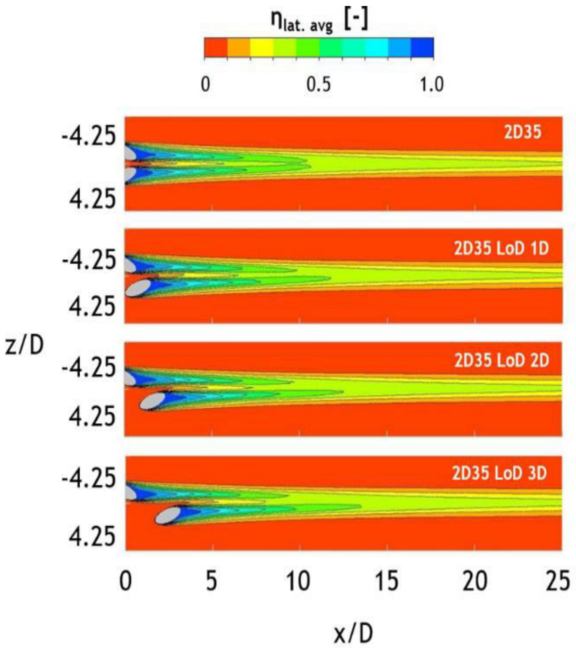


**Figure-6.** Comparison of film cooling effectiveness contour between baseline and LoD cases.

Figure-7 indicates that the longer the LoD, the higher the effectiveness of the film cooling further downstream. Based on the result, the baseline design shows the highest peak point of film cooling effectiveness whereby the longer the LoD between the holes, the lower the peak point of effectiveness. Although the baseline design has the highest peak point, it decays rapidly as it moves in x-direction.

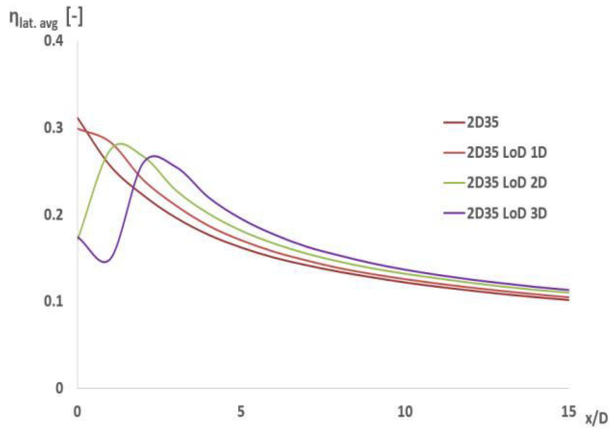


**Figure-7.** Laterally averaged film cooling effectiveness for LoD cases.

**Upstream ramp**

As for the upstream ramp, there are two designs that have been proposed; triangular ramp (Tri Ramp) and rectangular ramp (Rec Ramp). The idea of upstream ramp is to modify the interaction between the approaching boundary layer flow and the film cooling jet to increase the film cooling effectiveness. Figure 8-10 demonstrated the comparison of film cooling effectiveness contour for upstream cases with baseline case for M=0.5. Compared to the baseline design, upstream ramp designs shows better lateral spreading of the coolant upon exiting holes. In addition, the implementation of the upstream ramp cause an excessive coolant at the exit holes whereby some back flow of the coolant thus the film cooling effectiveness near exit holes region is increased. Figure-11 and Figure-12 shows the vector of the mixture of the mainstream and the coolant on XY and XZ plane.

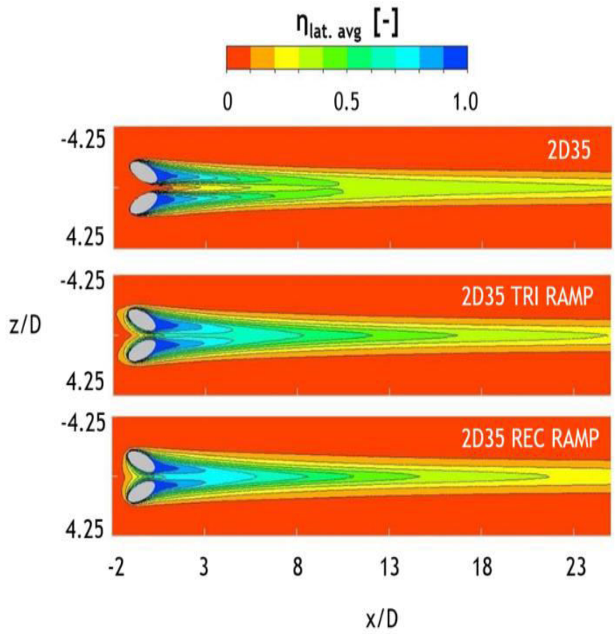


**Figure-8.** Comparison of film cooling effectiveness contour between baseline and upstream ramp (M=0.5).

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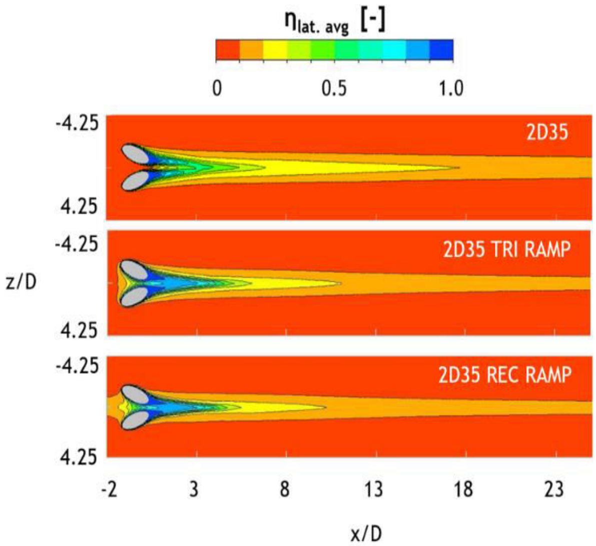


**Figure-9.** Comparison of film cooling effectiveness contour between baseline and upstream ramp (M=1.0).

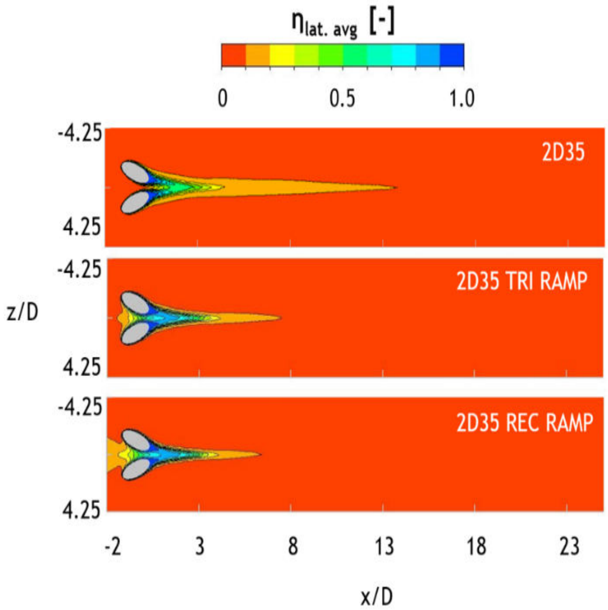


**Figure-10.** Comparison of film cooling effectiveness contour between baseline and upstream ramp (M=1.5).

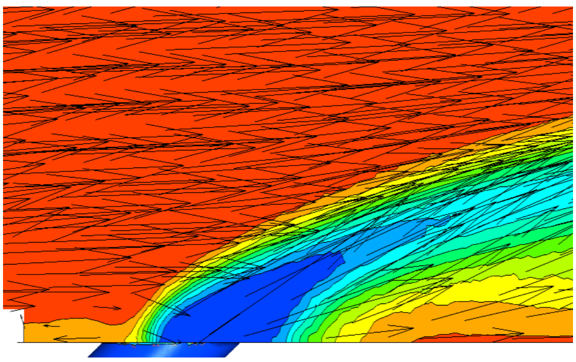

**Figure-11.** Back flow vector on XY plane.

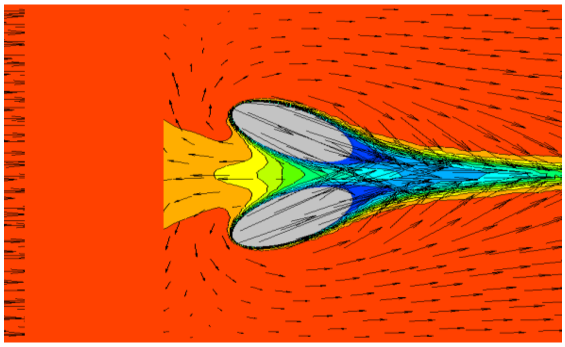

**Figure-12.** Back flow vector on XZ plane.

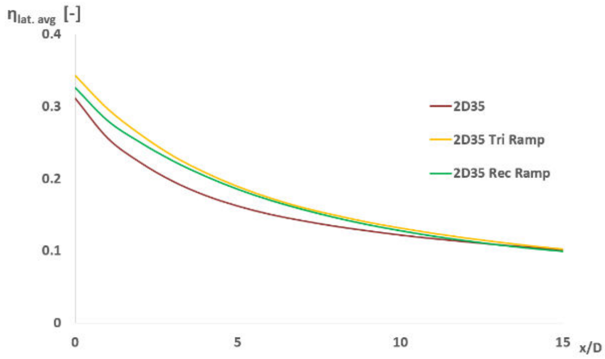


**Figure-13.** Laterally averaged film cooling effectiveness for upstream ramp cases.

Based on the figure, the arrow means the flow of the stream however at near the exit hole there are arrows which flow opposite to the x-direction which proves the back flow of the coolant for upstream ramp case (Tri Ramp M=1.0).As for the lateral averaged film cooling effectiveness for upstream ramp cases, Figure-13 shows the pattern for both upstream cases in comparison with the baseline design. At x/D ≈ 15 all designs including the baseline have exactly same effectiveness and upstream ramp design decays faster than the baseline. The graph also demonstrates that 2D35 Ramp Tri produces the highest effectiveness atthe exit hole region and until x/D ≈ 10.

**LoD and upstream ramp 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 starts from 0D to 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-14 where the result for LoD cases shows a slight improvement as the LoD become longer. Meanwhile, for upstream ramp cases, both design indicates an improvement which is dominated by 2D35 Tri Ramp design by increasing nearly 0.01 compared to the baseline design. As for the other blowing ratios, the pattern for M=1.0 and M=1.5 is quite similar whereby the most area covered is shown by 2D35 LoD 3D case. The upstream ramp cases have low area average on high blowing ratio due to the backflow of the coolant.

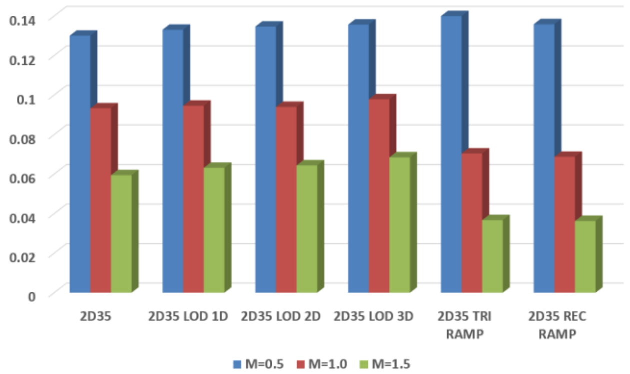


**Figure-14.** Area average film cooling M = 0.5, 1.0 and 1.5.

**LoD and upstream ramp 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-15 and 16 shows the vorticity plot comparison for 2D35 LoD and ramp cases at distinct location, x/D = 5 using a different blowing ratio. 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 an information on one more phenomena that known as lift off phenomena. When the hot gases from the mainstream meets the coolant, there 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 decreasing. All considered cases demonstrate nearly same pattern where the lift off phenomena can be seen as the magnitude of the vortex is getting higher as the blowing ratio increasing

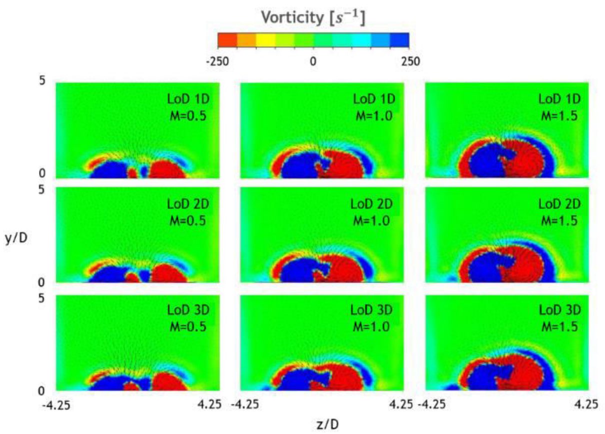


**Figure-15.** Vorticity counter plot for 2D35 LoD cases; x/D=5.

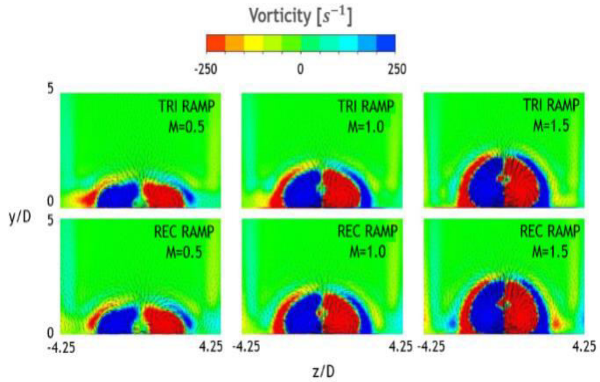


**Figure-16.** Vorticity counter plot for 2D35 upstream ramp cases; x/D=5.

**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, Reynolds number Re = 11000 and also there are six different cases that have been considered; 2D35, 2D35 LoD 1D, 2D35 LoD 2D, 2D35 LoD 3D, 2D35 Tri Ramp and 2D35Rec Ramp. The conclusions of the present study are as follows:

- The implementation of LoD and upstream ramp for double cylindrical holes geometry shows improvement in term of film cooling effectiveness compared to the baseline design.
- By having an upstream ramp of the cooling holes, the approaching boundary-layer flow is deflected away from the surface and the film cooling jet thus the diverted layer flow serves as a blocker that confines the cooling jet next to the surface and increases its lateral spreading.
- In comparison for all cases, case 2D35 with triangle shaped upstream ramp 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
- 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.

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