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Simulation of Film Cooling in the Leading Edge Region of a Turbine Blade Using ANSYS CFX

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Abstract – *Film cooling is one from the many of cooling techniques applied to turbine blade. Gas turbine uses film cooling technique to protect turbine blade from direct exposure to hot gas to avoid wear and defects of the blade. The focus of this investigation is to investigate the effect of embedding three different depths of trench at coolant holes geometry. Comparisons are made at three different blowing ratios, which are 1.0, 1.25 and 1.5. Three configurations of leading edge with different depths, which are Case A (0.0125D), Case B (0.0350D) and Case C (0.0713D), were compared to leading edge without trench. The result shows that as blowing ratio increased from 1.0 to 1.2, the film cooling effectiveness increased for leading edge without trench and also for all cases. However, when the blowing ratio increased to 1.5, the film cooling effectiveness decreased for all cases. Overall, Case B with blowing ratio of 1.25 has the best film cooling effectiveness with a significant improvement compared to leading edge without trench and with trench for Case A and Case C.*

Keywords: Trench effect, Film cooling, Turbine blade

1.0 INTRODUCTION

Thermal efficiency of gas turbine engine can be efficiently improved by increasing the temperature of turbine inlet. This high operative temperature affects the durability of blade. Therefore, in order to prevent damage to the blade, film cooling techniques have been developed. Applying the concept of film cooling effectiveness can avoid the blades from failure or defect. This study focuses on the effect of different depths of trench. 3D computational fluid dynamics (CFD) simulation using ANSYS software will be performed to determine jet-mainstream interactions to better understand film effectiveness distributions. In this study, the investigation was performed at a single mainstream Reynolds number based on film-hole cylinder diameter of 8,550 at four different blowing ratios (1.0, 1.25, 1.5 and 2.0). The result was then validated with a journal numerical study on a flat plate and leading edge film cooling [1]. There are a lot of factors that should be considered to increase film cooling effectiveness, such as inclination of the holes that are connected with the plenum. Yuen and Martinez-Botas [2] reported a study where three angles (30°, 60° and 90°) were tested. From the result, the best cooling characteristics was observed at 30°. With the objective to look for a better film cooling technique, Lu *et al.* [3] investigated the effect of slot exit area and edge

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shape on film effectiveness measurements made on a flat plate. They found that a straight-edge exit performed the best at a blowing ratio of BR=1.0, whereas a ramped exit enhanced the adiabatic effectiveness levels at lower blowing ratios. Baldauf *et al.* [4] observed that initial increase in η with increasing BR is expected due to the greater mass flow of coolant, whereas the decrease in η for $BR \geq 0.85$ is due to the coolant jet separating from the surface [4]. David G. Bogard [5] mentioned that film effectiveness can be improved if the exit of the hole is expanded so that coolant is slowed through a diffuser.

2.0 METHODOLOGY

In this study, ANSYS software was used to simulate film cooling at the leading edge involving fluid flow and heat transfer based on simulation. Blowing ratio, *BR*, is defined as the ratio of mass flux of the mainstream and the coolant. It is expressed as:

$$BR = \frac{\rho_c V_c}{\rho_\infty V_\infty} \tag{1}$$

Film cooling effectiveness is defined as:

$$\eta = \frac{T_{aw} - T_\infty}{T_c - T_\infty} \tag{2}$$

Mainstream conditions were maintained in all cases, and coolant flow rate was altered to change the velocity of coolant. Coolant temperature was set at 321K and mainstream temperature was fixed at 291K. The Reynolds number for the study was 8550 based on the mainstream velocity and the diameter of the cooling hole.

A model was constructed using SOLIDWORKS software. Figure 1 shows the computational domain of semi-cylindrical leading edge model with a flat alter body. Within the cylindrical wall of 80 mm diameter (D=10d) were plenum and three rows of film cooling holes arranged in a staggered fashion. The diameter of each hole was 8 mm (d=8 mm). The inclination angle of holes was 30° relative to span-wise direction.

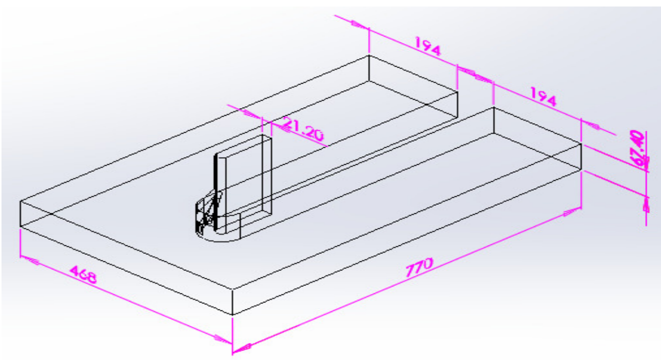


Figure 1: Schematic for the leading edge

Periodic condition was imposed to the span-wise direction so that only three film cooling holes need to be examined. Figure 2 shows the separation angle between hole 1 and hole 2 in the x-y plane of 30° and the separation angle between hole 2 and hole 3 in the x-y plane of 35°. The pitch between the holes was 31 mm. Figure 3 illustrates three different cases of trench embedded at coolant exit holes.

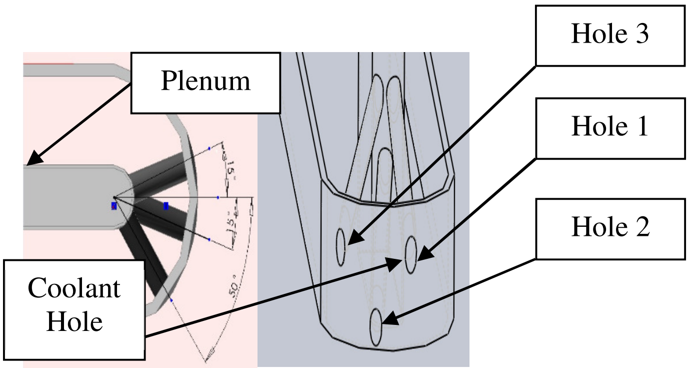
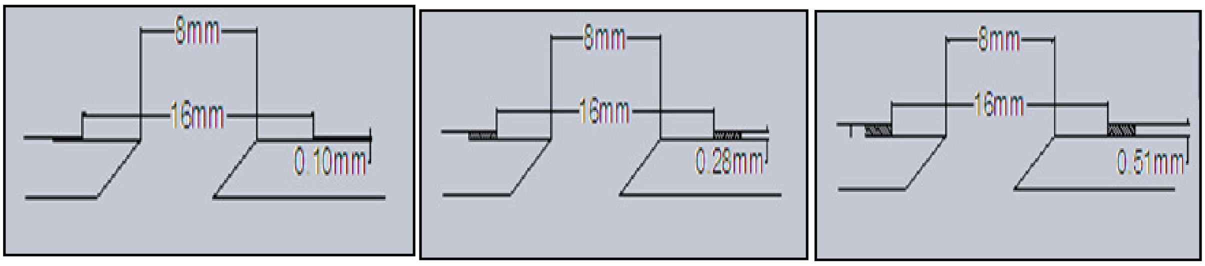


Figure 2: Angles for coolant holes



Case A (0.0125D) Case B (0.0350D) Case C (0.0713D)

Figure 3: Three configurations of leading edges with different depths

In the computational domain, boundary conditions were set at the domain. Mainstream conditions were maintained for all cases. The magnitude of coolant velocity varies by altering blowing ratio for each case.

Table 1: Boundary conditions and numerical set up

Item	Physical Properties
General Condition	Steady state
	Incompressible
	Non radiation
Turbulence Model	k-ω SST Model
Inlet	Mainstream temperature (K) 291
	Coolant (K) 321
	Mainstream inlet velocity (m/s) 15.955

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3.0 RESULTS AND DISCUSSION

The current numerical work was validated by comparing the results with the numerical data from the numerical study on flat plate and leading edge film cooling [1]. This was done by laterally observing the average film cooling effectiveness at the leading edge without trench case. From Equation 3, the standard deviation between simulation data was about 0.08, which was relatively small, thus giving high validity to the present simulation. Hence, the current simulation approach was satisfactory and validated. The simulation and experimental averaged effectiveness distributions are shown in Figure 4.

$$\sigma = \frac{\sqrt{\sum\left(U_{x_{i,num}} - U_{x_{i,\exp}}\right)^2}}{n} \tag{3}$$

where

$U_{x_{i,num}}$ = local numerical averaged effectiveness

$U_{x_{i,\exp}}$ = local experimental averaged effectiveness

n = number of data

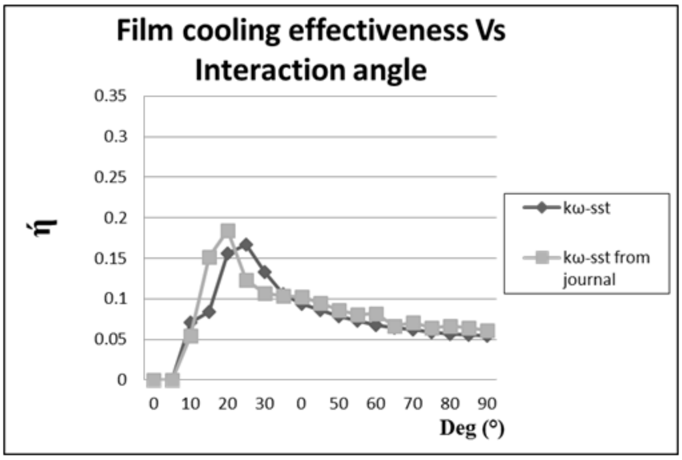


Figure 4: The validation plot for averaged effectiveness between simulation and experiment at BR=1.0

Three models of leading edges with different depths of trench and leading edge without trench were tested under difference blowing ratios (BR) of 1.0, 1.25 and 1.5. Figure 5 shows the quantitative values for film cooling effectiveness at BR=1.0. It shows that the entire leading edge configuration with trench yielded much higher film cooling effectiveness values compared to leading edge without trench. However, the film cooling effectiveness values for all cases of leading edge with trench was almost similar each other. It shows that the effect of different depths of trench height on film cooling effectiveness was small at BR=1.0. Figure 6 shows the coolant spread on the leading edge surface. From the figure, it can be observed that there is more coolant spreading on the leading edge surface for leading edge with trench compared to the leading edge without trench.

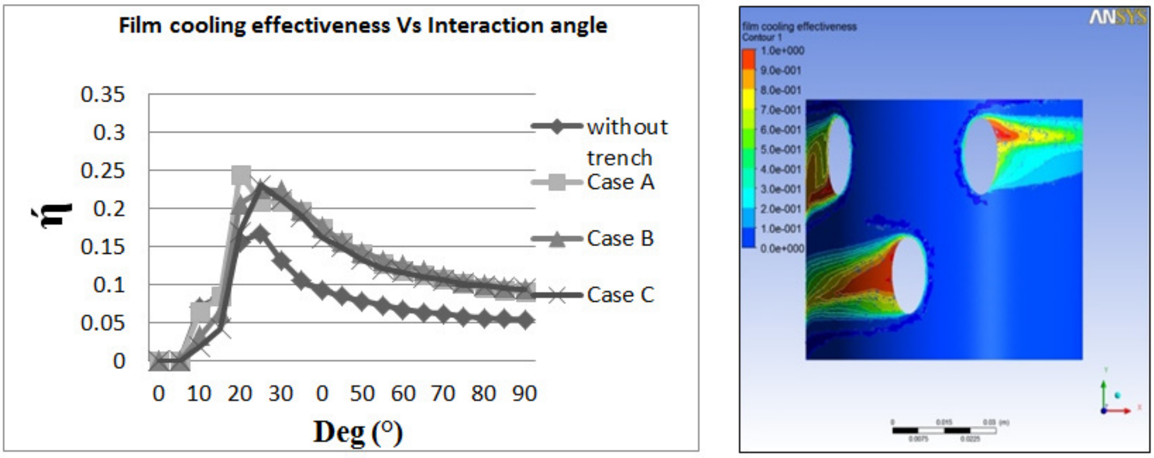
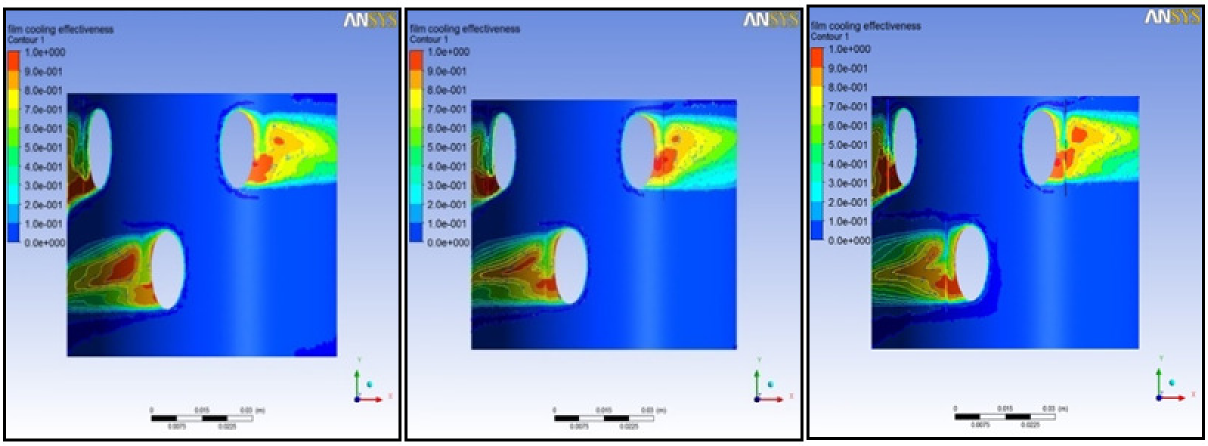


Figure 5: Lateral film cooling effectiveness at BR=1.0 (left) and leading edge without trench(right)



Case A Case B Case C

Figure 6: Distributions of film cooling effectiveness for leading edge without trench, Case A, Case B, and Case C at BR=1.0.

The effect of embedding trench at the leading edge is represented by Figures 7 and 8. The velocity vector shows that for leading edge without trench, the jet coolant directly exited the coolant holes, which was then mixed with the mainstream velocity. This phenomenon presents low averaged film cooling effectiveness to the leading edge without trench. For example Case

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A, it appears that the coolant exiting the holes and then the coolant jet filled the trench before being spread outside the trench area.

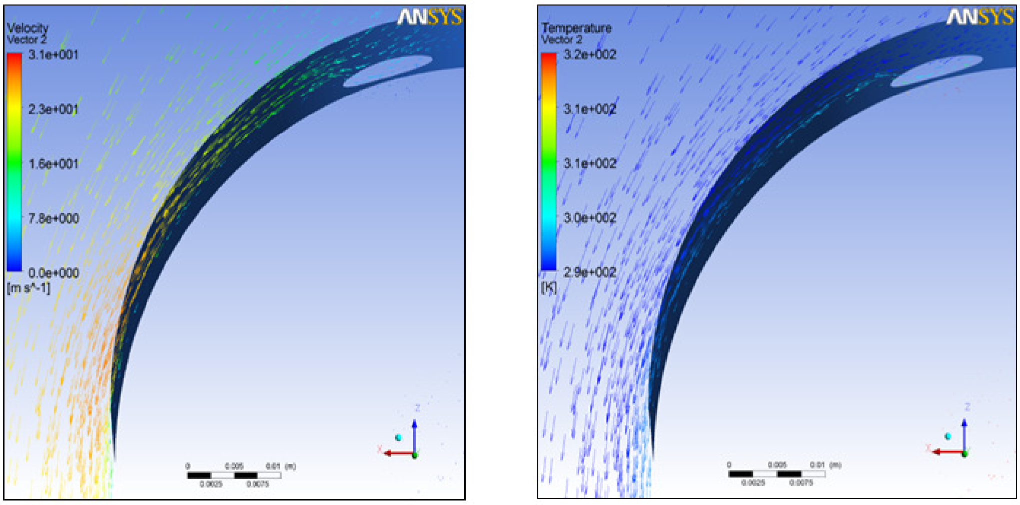


Figure 7: Velocity vector (left) and temperature (right) for leading edge without trench at BR=1.0.

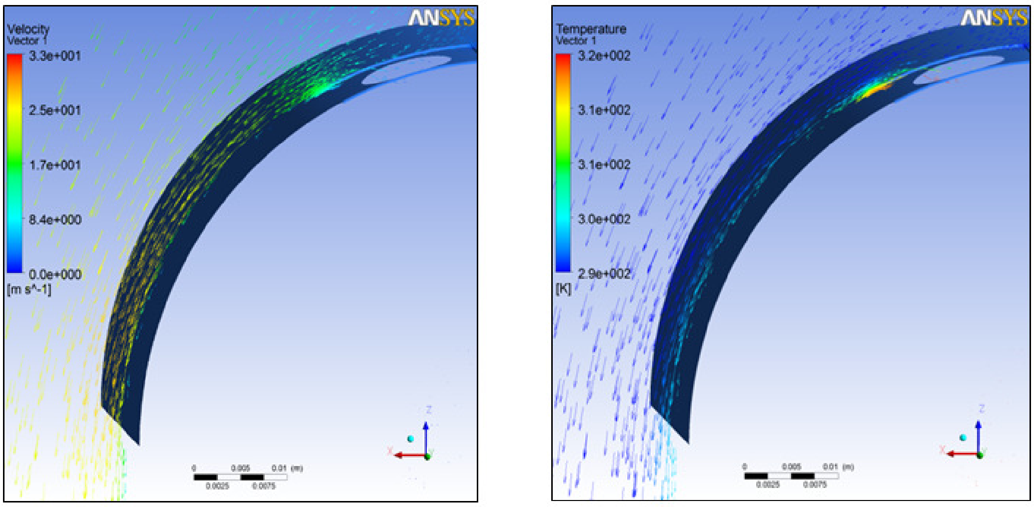
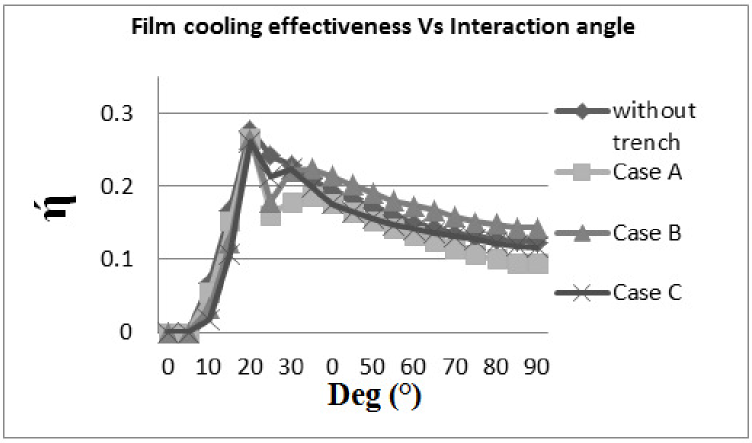


Figure 8: Velocity vector (left) and temperature (right) for leading edge with trench at BR=1.0.

When the coolant jet struck along the trench edge, it affected the change of velocity. The velocity after the coolant jet struck the trench edge was higher compared when the coolant jet did not strike the edge upon exiting. Thus, the coolant spread outside the trench and covered larger area at the leading edge. It was observed that less interaction occurred between coolant jet and mainstream in the jet exit region. These results in higher effectiveness at the jet exit. However, in the downstream, the film thickness became lesser and led to lower effectiveness.

As the BR increased to 1.25, the film cooling effectiveness increased for all cases including the leading edge without trench. As can be seen in Figure 9, all the values of film cooling effectiveness increased, where the highest film cooling effectiveness was achieved in Case B, followed by the leading edge without trench, Case C and Case A. This phenomenon happened because as the blowing ratio increased to 1.25, the coolant velocity also increased, thus enhanced the film cooling effectiveness for leading edge without trench compared to the blowing ratio 1.0. From the graph, as the blowing ratio increased, the film cooling effectiveness also increased. This phenomenon is proven by looking at the film cooling effectiveness values for the leading edge without trench at blowing ratio of 1.25 and compared to the value of film cooling effectiveness for the leading edge without trench at blowing ratio of 1.0. Hence, it is shown that when the blowing ratio increases, the effectiveness of film cooling at the leading edge without trench also increases.



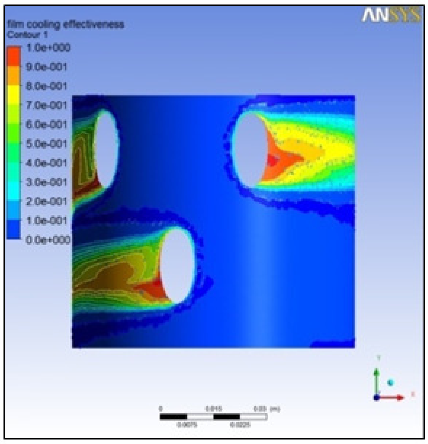


Figure 9: Lateral film cooling effectiveness at BR=1.25 (left) and leading edge without trench (right)

For Case A, Case B and Case C, the film cooling effectiveness did not change significantly. The highest film cooling effectiveness was observed for Case B, whereas the lowest film cooling effectiveness was determined for Case A. This concludes that when the coolant enters the medium trench with medium blowing ratio, it will produce the best film cooling effectiveness. From Figure 10, it can be seen that for each Case A, Case B and Case C, as the coolant exiting the holes, the coolant jet will fill the trench before exiting to the leading edge surface. At some point, when the coolant jet fills the trench completely, it will strike the trench edge, then the velocity of the coolant jet becomes higher and causes the coolant to spread widely. Consequently, it causes higher film cooling effectiveness, and this phenomenon is explained by Figures 7 and 8. It is observed that the effects of trench Case B at blowing ratio 1.25 helped the coolant jet to spread widely as compared to all cases. When the coolant spread widely, more interaction occurs between the coolant jet and the mainstream in the jet exit region. This results in higher effectiveness at the jet exit. However, in the downstream, the film thickness becomes thinner and lower.

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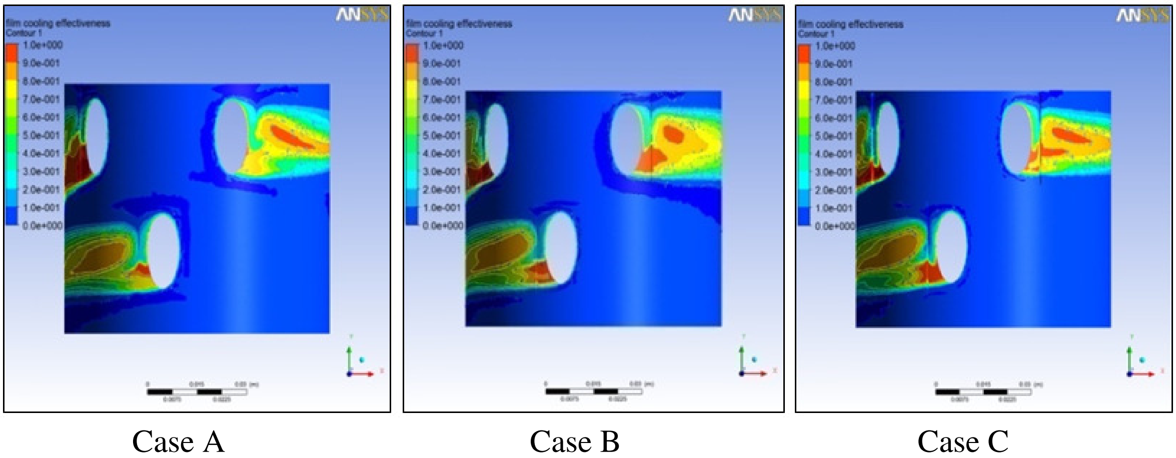

Figure 10: Distributions of film cooling effectiveness for leading edge without trench, Case A, Case B, and Case C at BR=1.25

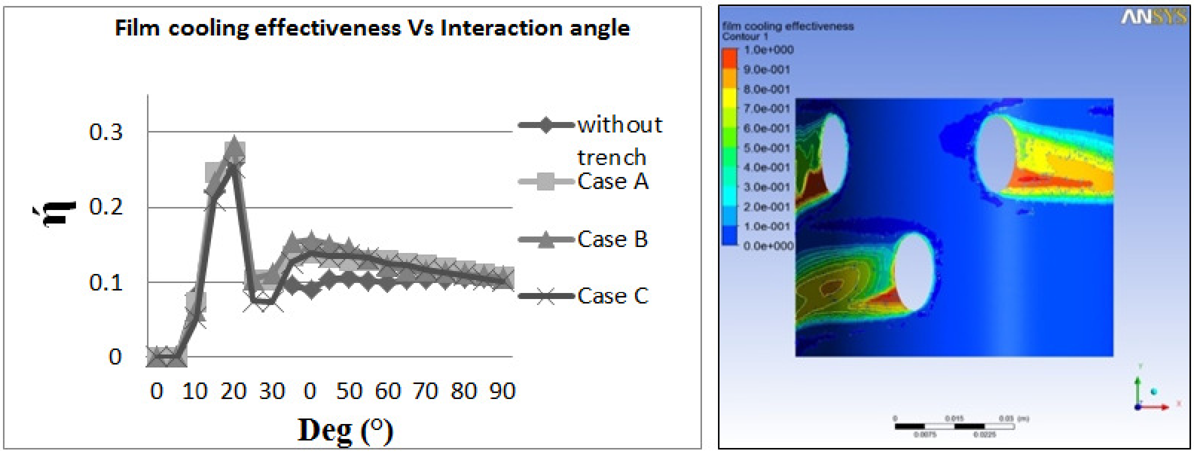

Figure 11: Lateral film cooling effectiveness at BR=1.5 (left) and leading edge without trench (right)

Figure 11 shows the result of film cooling effectiveness for blowing ratio 1.5. From the result, it is shown that the trends for the averaged film cooling effectiveness for all cases are almost similar. The highest film cooling effectiveness was observed for the leading edge without trench, followed by Case A, Case B, and lastly Case C. However, all the cases had lower averaged film cooling effectiveness compared to the blowing ratio of 1.25. The sudden decrease of film cooling effectiveness at angle 20° to 30° is due to the coolant jet velocity phenomena. As can be seen from Figure 12, for blowing ratio 1.5, the coolant jet velocity is higher compared to the blowing ratio 1.0 and 1.25. When the coolant jet exits the coolant hole with high velocity, only a small amount of coolant filled the trench. This is due to the higher jet effect that which mixed the coolant directly with the mainstream rather than spreading into the trench. In other words, only a slight amount of coolant strikes the trench wall, thus the coolant does not fully cover the majority of the area. Therefore, it produces low film cooling effectiveness.

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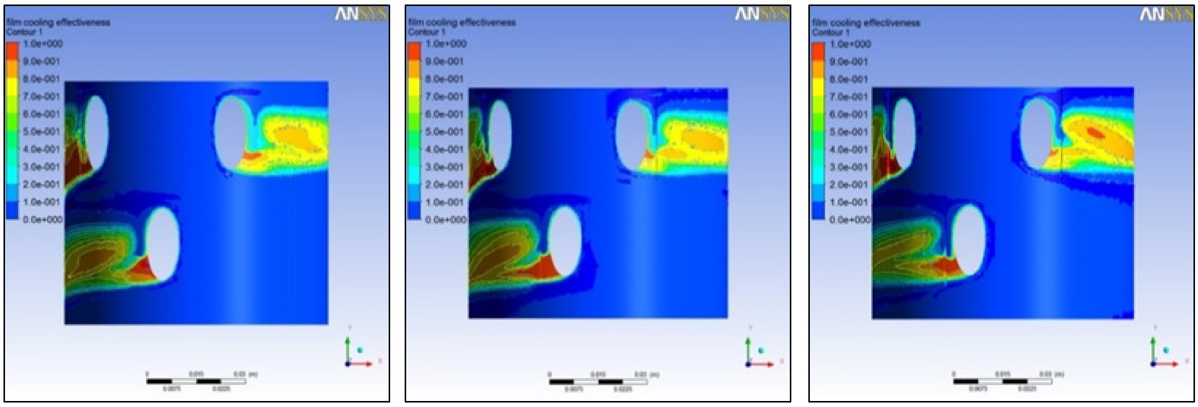

Case A Case B Case C

Figure 12: Distributions of film cooling effectiveness for leading edge without trench, Case A, Case B, and Case C at BR=1.5

4.0 CONCLUSION

Three types of trenches with different depths were tested with three blowing ratios of 1.0, 1.25 and 1.5. The result shows that with medium depth of trench, the coolant spreads widely on the leading edge and covers a larger area. With this characteristic of coolant spreading, the leading edge with medium depth of trench enhances film cooling effectiveness as compared to all cases with and without trench. This means the depth of trench does affect the film cooling effectiveness. Hence, it can be concluded that the film cooling performance can be significantly improved by controlling the blowing ratio and the depth of trench. It is noted that the blowing ratio and depth of trench has a very strong effect on film cooling effectiveness.

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