An Experiment Investigation of Film Cooling Effectivenes of Sister Hole of Cylindrical Shaped Hole Film Cooling Geometry on A Flat Plate Surface

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Abstract

Gas turbines are widely used nowadays for aircraft propulsion and in land-based power generation or in the industrial application. The operating temperature of gas turbine has to be increased in order to increase their effectiveness. Thus, a cooling method known as film cooling is introduced to cool down the high operating temperature of the gas turbine. Film cooling is one of the effective methods in reducing the heat load to a turbine airfoil. This method is cost effective and by far the most common and widely researched method in the industry. Film cooling effectiveness plays a vital role in modern gas turbine technology. This present study will focus on sister holes that are attached to the primary holes at shallow angle of 30°, with 4 different blowing ratios ranging from 0.5 to 2.0. The roles of the different in blowing ratios are to observe the different values of film effectiveness presented by the sister holes design and to select the most effective blowing ratio that suits the design at shallow angle. From the results obtained, the usage of sister holes with shallow angle further increases the film cooling effectiveness particularly at low blowing ratio.

I. INTRODUCTION

Gas turbines are used for aircraft propulsion and in land-based power generation or in the industrial application. When the turbine inlet temperature increases, the thermal efficiency and power output of gas turbines increases. This leads to the increase of demand for more efficient gas turbine engines entails the needs for increasingly advanced material and cooling technique for gas turbine components to overcome the increases in rotor inlet temperature. Han, Dutta & Ekkad [1] stated that the advanced gas turbine machines operate at high temperature around 2500-2600˚F. Such increased temperature often exceeds the metallurgical limit of the turbine blades, making the use of film cooling necessary. Thus, a cooling method such as the usage of film cooling is needed to protect the turbine blades and its effectiveness is to be of concerned the most. Even though many other techniques exist, by far film cooling is the most common and widely researched method in the industry.

Film cooling is one of the effective methods in reducing the heat load to a turbine airfoil. The vane and blade of the turbine have multiple row film cooling holes. The first stage turbines vanes and blades of most high performance heavy duty gas turbines operate at hot gas temperatures higher than the melting point of the most advance single crystal material available today. It has to be cooled

down significantly below its typical melting temperature of between 800°C to 1000°C. The aerodynamic and film cooling effectiveness characteristic of a first stage turbine high lift vane and its corresponding downstream blade is investigated in two ways, which is by two different high speed linear cascades and by numerical investigation.

The main focus of this research is to investigate the film cooling effectiveness for primary hole of 30° with additional of sister holes through experiment. It is then analysed and compared with the data obtained from past research.

II.   LITERATURE REVIEW

A. Effects of blowing ratio

Many researchers found out that blowing ratio plays a significant factor in film cooling effectiveness. The higher the blowing ratio, the higher the film cooling effectiveness. However, the effect of blowing ratios differs with other parameters. A study by Li et al. [9] found out that the film cooling effectiveness is proportional to the blowing ratio among 0.6 – 2.0. The result from their study demonstrates that the film cooling efficiency is the largest when the blowing ratios is around 0.6 – 2.0 and the cooling effectiveness is the best when the blowing ratio is at 2.0. As the blowing ratio increases, the film cooling become narrow, and the effectiveness will declined at first yet the increment of the effectiveness can be seen as the blowing ratio increases. Nonetheless, the film cooling efficiency become less when the blowing ratio value is greater than 4.0. This statement is supported by Goodro et al. [10] in their research when they found out that there is a slight increase in the film effectiveness when the blowing ratio is increased from 2.0 to 5.0 but there is no further considerable improvement when the blowing ratio is increased to 10.0.

A research by Goldstein, Ecket-t, Eriksen and Ramsey [11] shows the effect of blowing ratio on centreline film-cooling effectiveness for a row of a simple injection holes inclined at 35˚ in the stream-wise direction. The values for the centreline effectiveness are plotted at different X/D locations. Their research shows that the film effectiveness increases with the increases in blowing rate at near injection hole locations as in X/D = 5.19. Then, it reaches a peak and drops with further increase in blowing ratio. The profiles become more horizontal or flatter as it is farther away from the injection hole. They found out that at high blowing ratios, the distances far downstream of injection show similar effectiveness values as locations immediately downstream of injection. A more recent study made by Yang et al. [12] who completed an investigation on the arrangement of film hole and they found out that the blowing ratios have great effects on the film cooling effectiveness. From their results, it shows that the film cooling effectiveness increased with the increased in blowing ratio. However, it decreased gradually in the direction of the mainstream.

B. Effects of injection angle or inclination angle

Compound-angle injection provides higher film cooling effectiveness than a simple-angle injection for one row of holes. Lingrani et al. [13] compared the effect of hole angle for two staggered rows. They found out that the simple-angle data are lower compared to the compound-angle data. The film cooling effectiveness for compound-angle injection is higher due to stronger lateral momentum and more spreading of jets, providing higher effectiveness over a larger spanwise region. In contrast, the simple-angle film cooling mostly along the hole in the downstream direction, with very little lateral spreading of jets.

Another study on compound-angle is done by Nasir, Ekkad & Acharya [14]. Their work are made by adding a compound angle to a hole with large streamwise angle produces significant variations in the detailed film effectiveness distributions and enhances local heat transfer coefficients. Based on the result of their study, they found out that the film cooling effectiveness is generally lower for a large streamwise angle of 55˚ compared to the typical shallow angle of 35˚. Their findings indicate

that the overall performance has improved with the use of compound angle injection with large streamwise angle hole.

A summary of a more comprehensive review of the effect of varying the hole angle is made by Bogard [8]. In his conclusion, the film effectiveness performance for 90˚ compound angle holes is higher compared to of 0˚ streamwise oriented angle holes. He added that the term "compound angle" injection is referred to when the coolant hole is angled to the mainstream direction. The compound angle can be as much as 90˚ which is normal to the mainstream direction. He also added that the coolant injected at a compound angle is quickly turned into the mainstream direction, but will generally have a broader distribution of coolant. The maximum film effectiveness for the 90˚ compound angle holes was similar to that of 0˚ holes and occurred at a similar momentum flux ratio. Nevertheless, the 90˚ compound angle holes sustained high film effectiveness for very high blowing ratios.

C. Effects of different shape of the cooling hole

The shape of the film cooling hole is one of a vital role in determining the film cooling effectiveness. A study by Miao & Wu [20] shows that the geometrical shape of the cooling hole plays a significant effect to the adiabatic film cooling effectiveness. Their study is about the different types of cooling hole which includes cylindrical hole, simple angle hole (CYSA), forward diffused, simple angle hole (FDSA) and lateral diffused, simple angle hole (LDSA), evaluated at five different blowing ratios ranging from 0.3 – 1.5. The result of their study shows that LDSA hole would give a better later coverage of cooling stream on the flat plate surface and offer better cooling performance over other shape especially when the blowing ratios are increased from 0.3 – 1.5. Besides that, the LDSA shape is better is due to the structure of the LDSA that can reduce the momentum of the cooling flow at trailing edge of cooling holes. Hence, the streamwise penetration of the mainstream can be reduced.

Recent study made by Liu et al. [21] focused on the investigation of the effect of waist-shaped slot holes on film cooling compared to two types of discrete console hole. Their finding reveals that the waist-shaped slot holes produce greater cooling effectiveness in the midspan region between the adjacent holes due to the middle constriction structure of the waist-shaped slot holes and the coupled vortices make jets from waist-shaped slot holes.

The work of Asghar [23] investigated the effects of cooling hole shapes on film cooling effectiveness. The cooling hole shape in his study includes single row of circular holes, two staggered rows of semicircular-2 holes and two staggered rows of semicircular-1 holes. The result of his study for single row of circular holes is that the spatially averaged effectiveness increases with the increases in orientation angle 0˚ to 60˚. When the orientation is further increases to an angle of 75˚ or 90˚, the film effectiveness decreases but the decrease is insignificant.

D. Effects of sister holes

The sister hole concept was first put forth by Javadi et al. [30] whom proposed a simplified version of the models evaluated in the present study. In their research, a primary injection hole of diameter D is bounded by two smaller jets of diameter 0.5D slightly downstream to arrive at their "triple jet" approach to film cooling. In their study, the holes were rectangular in shaped and is injected perpendicularly to the mainstream which is less than ideal orientation for optimum effectiveness. Based in their initial results, the addition of these holes indicated dramatic improvements of film cooling effectiveness over standard single hole cooling.

Ely [31] made a numerical study on active film cooling flow control through the use of sister holes. The technique used in the study is by surrounding the primary hole injection hole by two or four smaller sister holes to actively maintain flow adhesion along the surface of the blade. The results from the study using the realizable k-ε turbulence model led to the determination that the use of sister holes greatly improves adiabatic effectiveness by countering the primary vertical flow

structure. The objective of his research is to determine the optimum configuration for the sister holes. He conclude that placing the sister holes slightly downstream of the primary injection hole improves the near-hole effectiveness whereas placing the sister holes slightly upstream of the primary hole improves downstream effectiveness. He found out that the approach of film cooling with sister holes provide viable improvements over standard cooling regimes.

III.   METHODOLOGY

A. Methodology flow chart
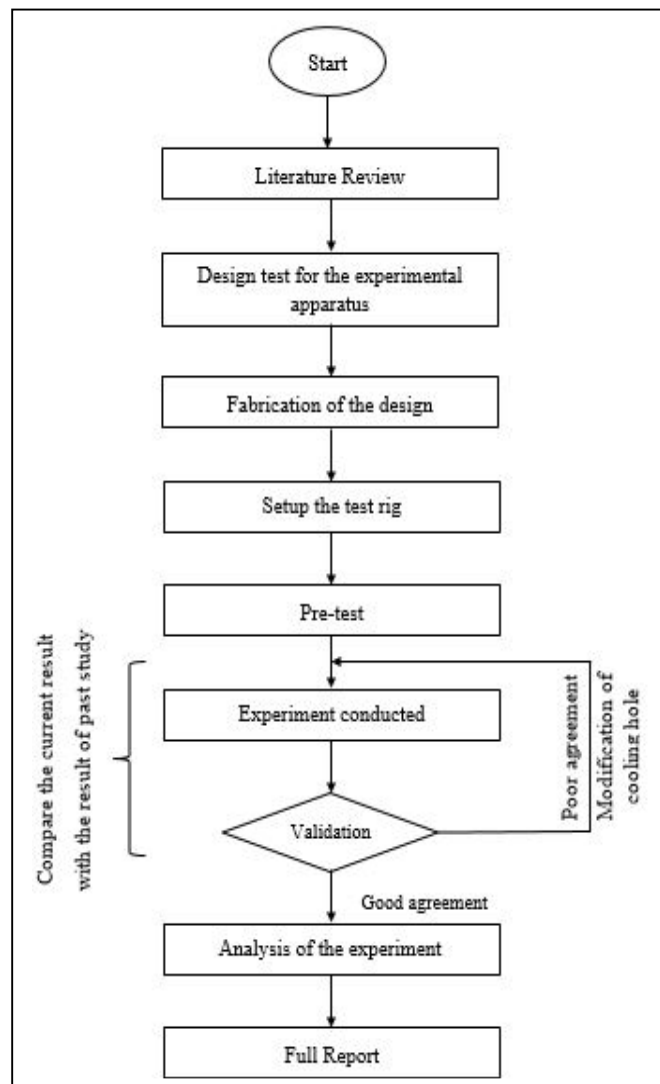
Figure 1: Flow chart of methodology

B. Experimental setup
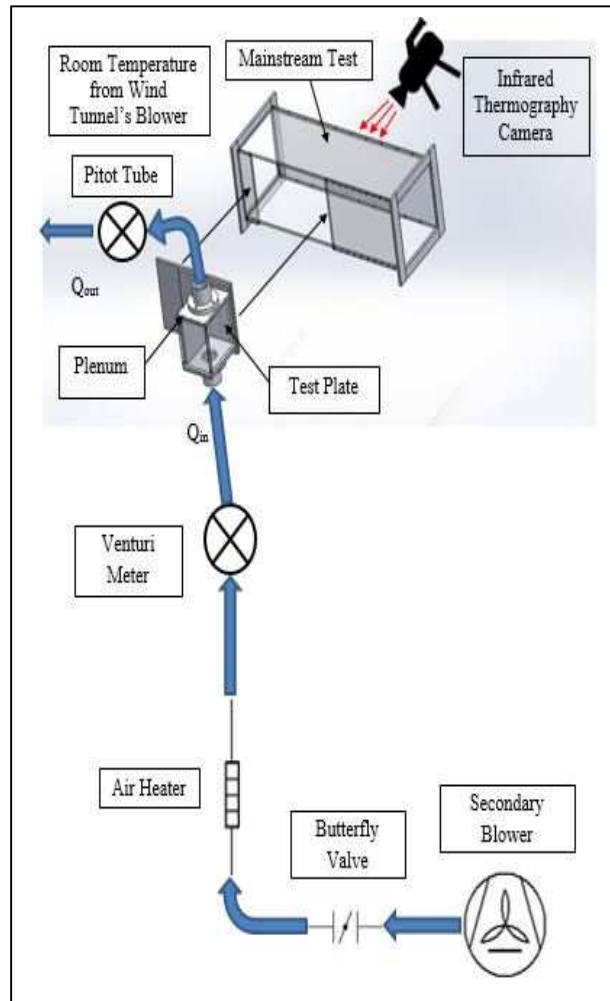
Figure 2: Layout of the experimental setup

C. Parameters measurement and plate geometries

Film cooling effectiveness η is used to express the film cooling phenomena quantitatively. Film cooling effectiveness is an important parameter to evaluate the film cooling performance where its value ranges from 0 to 1. The value of 1 would mean that a complete insulation of the blade from the hot gas path and a minimum value of 0 would imply that there is absolutely no protection from the temperature gradient of the hot gases. The performance of a film cooling technique was evaluated by means of adiabatic film cooling effectiveness as been given by Eq. (1).

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \tag{1}$$

T_{aw}, T_∞ and T_c are adiabatic wall temperature, mainstream temperature and secondary air temperature respectively. T_∞ and T_c were measured by thermocouples during the measurement while the wall temperature, T_{aw} was measured by infrared camera.

Blowing ratio, M in the coolant to the mainstream, are used in film cooling. It is one of affecting parameters studied in this research. Blowing ratio is defined as a scale the thermal transport capacity of the coolant which is generally increasing with the blowing ratio. In this research, the blowing ratios value is set with a range from 0.5 until 2.0. The blowing ratio is obtained using Eq. 2.

$$M = \frac{u_c \cdot \rho_c}{u_\infty \cdot \rho_\infty} \tag{2}$$

u_c, ρ_c, u_∞ and ρ_∞ are the coolant velocity, coolant density, mainstream velocity and mainstream velocity respectively.

The test plate is designed so that it can fit the window made at the test rig. This is to ensure that the test plate can be replaced with other test plate for other experiment. The test plate is 292mm long and 160mm wide with a fillet of 15° radius. The distance between one screws to another is 60mm whereas the distance of the screw to the edge of the plate is 20mm. The primary hole diameter is 8mm as shown in the Figure 3. The inclination angle for the primary hole is 30° and the distances outlet of the baseline center hole from the test plate edge is about 10mm. The holes were designed as close as possible to the measurement surface. Therefore, the data can be obtained more accurate. P/D ratio for baseline film hole is 3 whereas the L/D ratio used is 7.50. The length of the primary hole is 60mm.

The sister hole geometry is designed so that the sister holes are located downstream of the primary hole. The diameter of the sister holes pairing are 0.5D of the primary hole which is 4mm. The inclination for the sister holes are the same as the primary hole which is 30°. In addition, the orientation angle of the sister holes from the primary holes are 30°. The pitch diameter from one primary hole to another is 50mm whereas the distance from the primary hole to one sister hole is 9.79mm. The distance from the edge of the primary hole outlet with the edge of the sister hole outlet is 8.33mm.
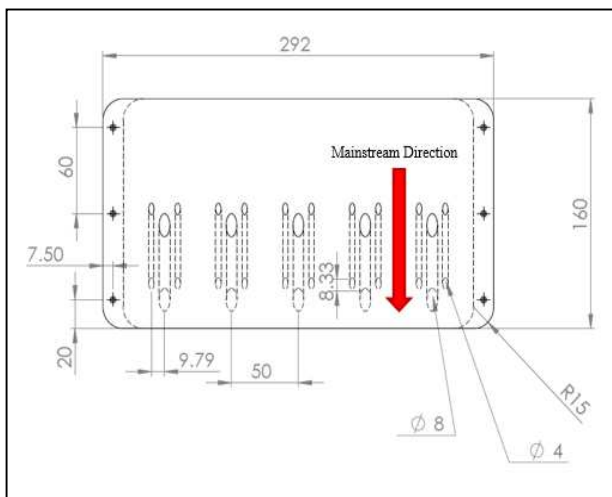

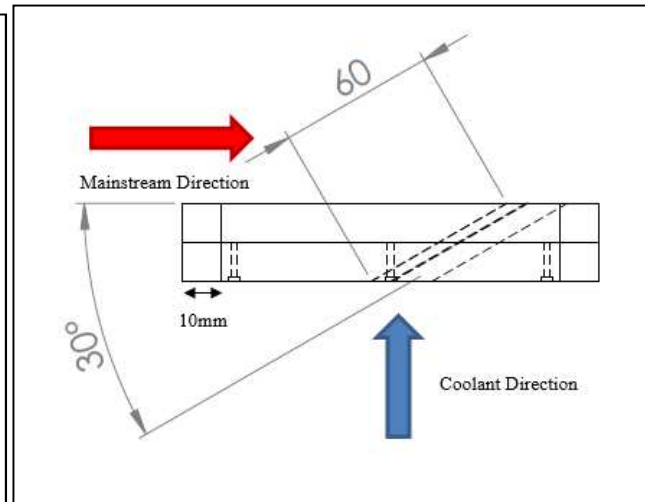**Figure 3:** Plan view of test plate with sister holes configuration

Figure 4: Side view of test plate with sister holes configuration
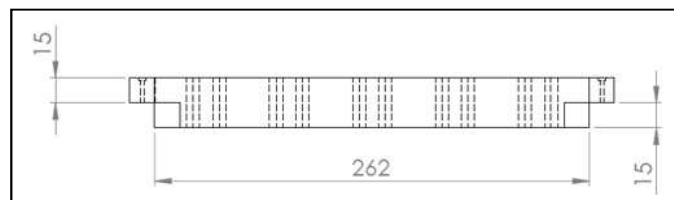

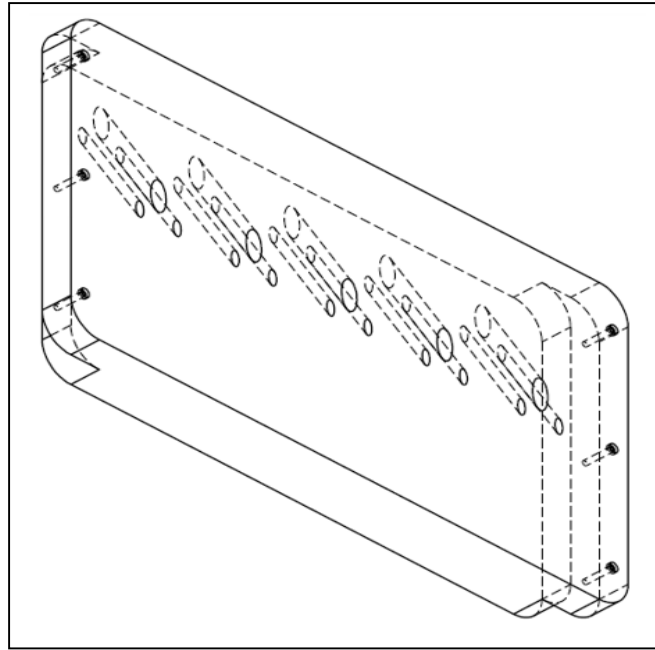**Figure 5:** Front view of test plate with sister holes configuration

Figure 6: 3D view of test plate with sister holes configuration

IV.   RESULTS AND DISCUSSION

The results of adiabatic film cooling effectiveness for 4 different blowing ratios will be displayed and are compared with each other to determine the optimum blowing ratio for the sister hole film cooling configuration. Besides that, the laterally averaged film cooling effectiveness and the centre-line adiabatic effectiveness along the streamwise distance are displayed for each blowing ratios. The temperature contour distributions are also displayed. The main focus of this study is to compare the current study of sister hole configuration with past study conducted and also to find out if there is any improvement of film cooling effectiveness from both studies.

A. Data measurement

Table 1 and Table 2 shows the all the data obtained. From the table, we can observe that with the increase in blower frequency, the blowing ratio also increases. Besides that, we can observe the increase in the velocity of the secondary flow with the increases in blower frequency. In addition, the mass flow rate also increase as the blower frequency increases.

Table 1: List of data obtained from the experiment

Blower Frequency (Hz)	Mainstream			Plenum	
	T_{main} (°C)	ρ_{main} (kg/m^3)	v_{main} (m/s)	T_{out} (°C)	ρ_{out} (kg/m^3)
6	28.5	1.17	15.3	51	1.0887
7	29	1.168	15.3	53.7	1.0797
13	29	1.168	15.3	50.6	1.0900
19	29.5	1.16	15.3	47.6	1.1004

Table 2: Experiment results for each frequency

Blower Frequency (Hz)	Experiment Results		
	m_{sec} (kg/s)	v_{sec} (m/s)	Blowing Ratio, M
6	0.0040	9.7086	0.5938
7	0.0071	17.4064	1.0572
13	0.0105	25.4498	1.5577
19	0.0136	32.7702	2.0226

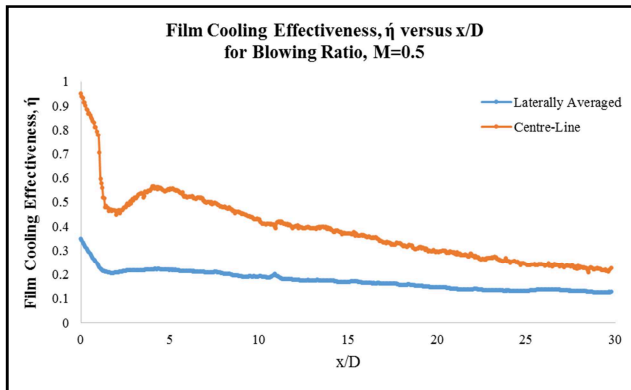*B. Temperature distribution and film cooling effectiveness results*

Figure 7: Film cooling effectiveness for blowing ratio, M=0.5
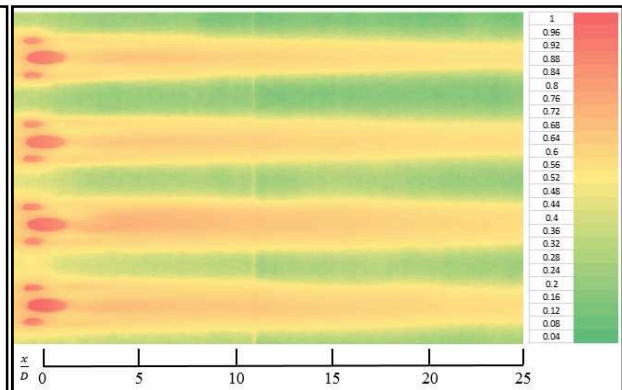

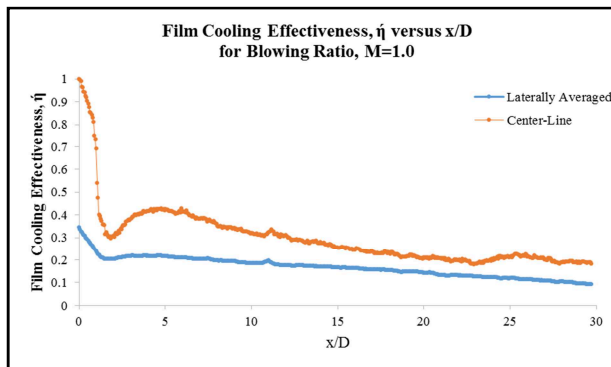**Figure 8:** Temperature contour and film effectiveness distribution for blowing ratio, M=0.5

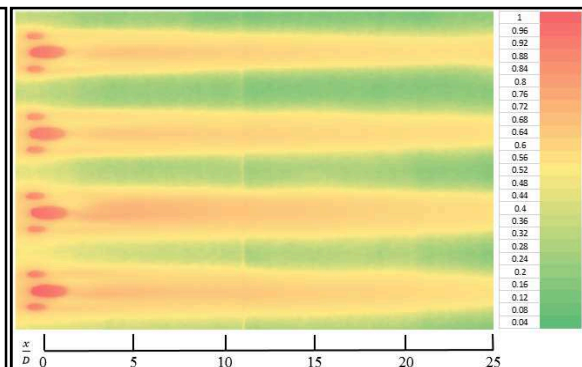**Figure 9:** Film cooling effectiveness for blowing ratio, M=1.0

Figure 10: Temperature contour and film effectiveness distribution for blowing ratio, M=1.0

Figure 7 shows both centre-line adiabatic effectiveness and laterally average film cooling effectiveness for blowing ratio of M=0.5 whereas Figure 8 shows the temperature contour and film effectiveness distribution extracted from the data. We can observe that the film effectiveness for both type is maximum at the exits of the cooling hole. However, there is a sudden decrease in center-line effectiveness between the regions of 0≤x/D≤5 and there is a slight decrease for the laterally averaged film effectiveness at the same region. For the temperature distribution contour for blowing ratio of M=0.5, the coolant temperature covers great spanwise distance as the temperature tip are not seen.

The trend for the graph of blowing ratio M=1.0 in Figure 9 is basically the same as M=0.5. There is a drop in both film effectiveness between region of 0≤x/D≤5 before it stabilised near the region of x/D=30. For the temperature distribution of blowing ratio of M=1.0, we can see that distribution contour at region of 25≤x/D≤30 becomes narrow or taper. Figure 10 shows the temperature contour and film effectiveness distribution extracted from the data.
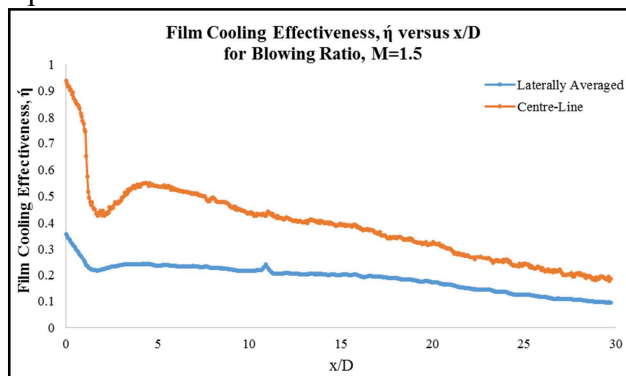

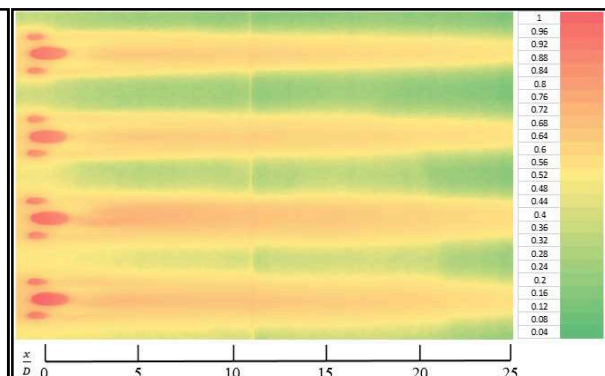**Figure 11:** Film cooling effectiveness for blowing ratio, M=1.5

Figure 12: Temperature contour and film effectiveness distribution for blowing ratio, M=1.5

From Figure 11, the trend of the graph of blowing ratio M=1.5 is the same as the blowing ratio of M=0.5 and M=1.0. There is a sudden drop of film effectiveness between regions of 0≤x/D≤5 before it stabilised further down the streamwise distance of x/D. There is a smooth region of cooling temperature that spreads between the regions of 0≤x/D≤20. Thus, that is why the distribution and intensity is much brighter compared to distribution and intensity of blowing ratio, M=0.5. Figure 12 shows the temperature contour and film effectiveness distribution extracted from the data.
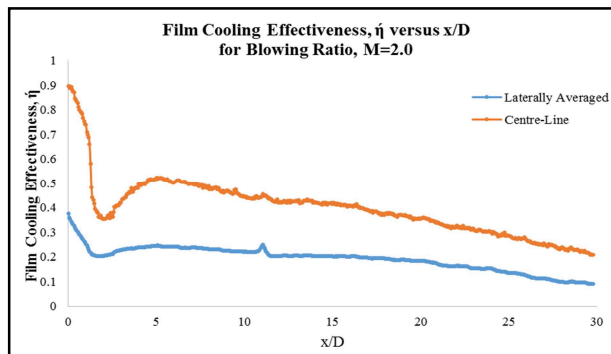

Figure 13: Film cooling effectiveness for blowing ratio, M=2.0
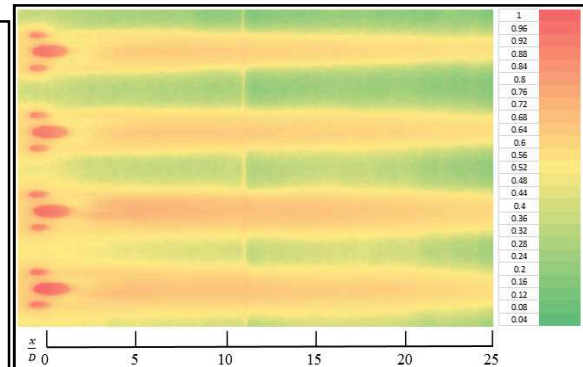
Figure 14: Temperature contour and film effectiveness distribution for blowing ratio, M=2.0

We can observe that the temperature distribution intensity decreased as can be seen in Figure 13 compared to when the blowing ratios are low. Figure 14 shows the temperature contour and film effectiveness distribution extracted from the data.
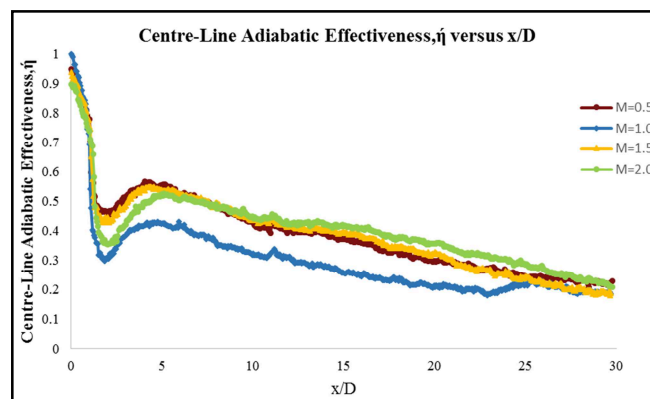

Figure 15: Centre-line adiabatic effectiveness for blowing ratios of M=0.5, M=1.0, M=1.5 and M=2.0

From the graph, we can observe a clear view of how the blowing ratio affects the adiabatic film effectiveness of the sister holes. For centre-line adiabatic effectiveness, we can see that for blowing ratio M=0.5, it has better overall film cooling effectiveness compared to others blowing ratio. This can be seen in the region of x/D>10. We can also observe that it has the least sudden drop of film effectiveness at the region of 0≤x/D≤5. On the other hand, the overall film effectiveness for blowing ratio M=1.0 is the least effective compared to others as the streamwise distance increases. However, its film effectiveness is the highest at near exit hole region. The film cooling effectiveness drops drastically between the region 0≤x/D≤5 as compared to other blowing ratios as can be seen from the figure.

In addition, we found out that the film effectiveness of blowing ratio of M=2.0 is better further down the streamwise distance of x/D. However, we found out that the film cooling effectiveness for blowing ratio M=1.5 is greater or better compared to the blowing ratio of M=1.0. This can be seen clearly from the graph as overall film cooling effectiveness for blowing ratio M=1.5 is better than blowing ratio of M=1.0.
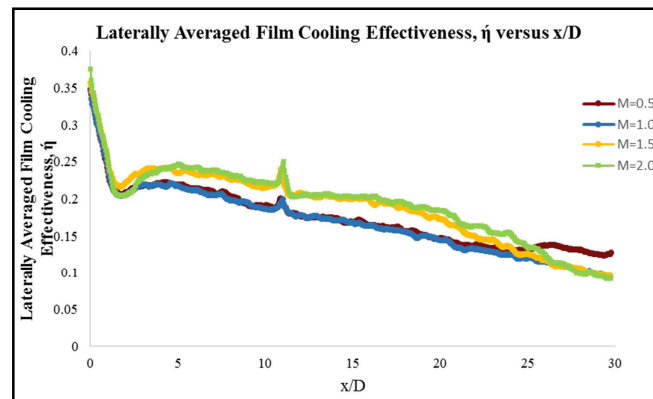
Figure 16: Laterally average film cooling effectiveness for blowing ratios of M=0.5, M=1.0, M=1.5 and M=2.0

From the graph, we can observe that the blowing ratio of M=2.0 has better laterally average film cooling effectiveness when it goes further down the streamwise distance. In addition, the laterally averaged film cooling effectiveness is the highest at blowing ratio of M=2.0 at the near hole region. However, as the streamwise distance increase, the laterally average film cooling effectiveness decreases. The overall laterally averaged film cooling effectiveness is better at high blowing ratio and decreases as the blowing ratio decreases. Nevertheless, at region between 25≤x/D≤30, we can see that the laterally averaged film cooling effectiveness of blowing ratio of M=0.5 is better compared to others. From the graph obtained, we can see a sudden increase of laterally average film cooling effectiveness for all blowing ratio at the region of 10≤x/D≤15. This is because there is a step between the test plate section and the mainstream wall of the test rig.

C. Comparison with past research

The results of current study will be compared with the result obtained through the study of Ely and Jubran [32]. Figure 17 below shows the result for centre-line adiabatic effectiveness for blowing ratio, M=1.0 for the current study and compared to the result of Ely and Jubran [32].
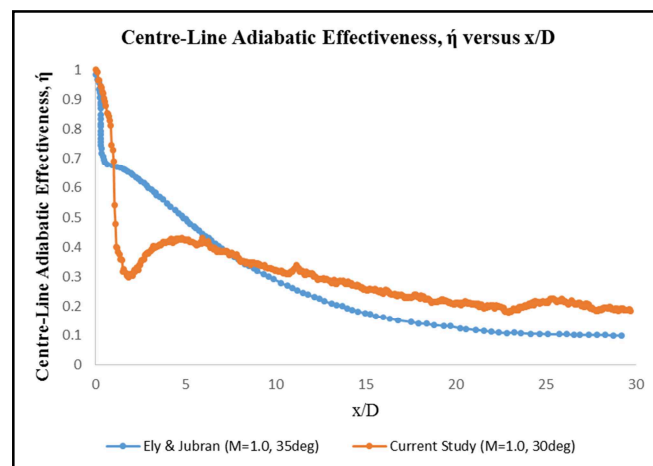

Figure 17: Comparison of centre-line adiabatic effectiveness for blowing ratio, M=1.0

From the graph, we can observe a big difference of overall center-line adiabatic film effectiveness. At the near region, Ely and Jubran study has the greater film effectiveness compared to the current study. The biggest different that can be seen is at the region of 0≤x/D≤5, where there is a sudden drop of film effectiveness between the current study and the past study. However, as the streamwise distance increases, the overall film effectiveness for current study is greater compared to past study. This can be seen after the region of x/D=10.
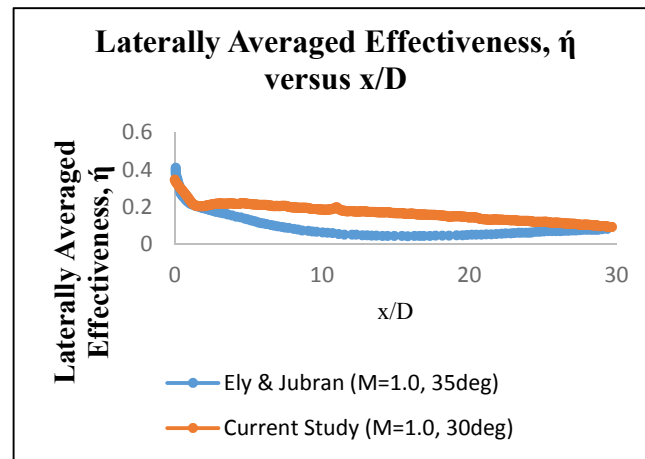
Laterally Averaged Effectiveness, ή versus x/D

Figure 18: Comparison of laterally averaged effectiveness for blowing ratio, M=1.0

The graph above shows the comparison of laterally averaged effectiveness for blowing ratio, M=1.0 between the current study and past study. From the graph, we can see that the current study has better overall laterally averaged effectiveness film effectiveness further down the streamwise distance compared to the past study. This can be seen clearly at the region $x/D \geq 5$. However, the laterally averaged effectiveness film effectiveness near the exit hole is greater and the value is higher compared to the result of the current study. This can be seen clearly at the region $x/D \leq 5$.

D. Discussion

The most important aspect of this study is to find out and compare the film cooling effectiveness with the addition of sister holes configuration of current with the past study conducted by Ely and Jubran [32]. For their study, the inclination angle of the sister hole is 35° and they are located 0.75D upstream and ±0.75D to each side of the primary hole. The primary hole diameter used is of D=12.7mm and the sister hole diameter is of 0.5D. For the current study, the sister hole diameter is 8mm and the sister hole is 4mm. The design and dimensions of the current study has been discussed in methodology. The sister hole configuration in both study is located upstream from the primary hole. The application of 4 different blowing ratios ranging from 0.5-2.0 are essential as to investigate the effect of film cooling effectiveness with the increases of blowing ratio.

When comparing the configuration of sister holes located upstream with sister holes located downstream, both have their advantages. For the upstream sister holes configuration, it has a greater laterally spread in the downstream direction as it dissipate less significantly. On the other hand, the downstream sister holes configuration will benefits the near hole region significantly for centre-line adiabatic film effectiveness. We also found out that the centre-line adiabatic film effectiveness for low blowing ratio of M=0.5 shows a notable performance improvements in the region of $5 \leq x/D \leq 10$ for upstream sister holes configuration.

From the results obtained, the film cooling effectiveness at near hole region increased greatly at low blowing ratio when the inclination angle or injection angle is reduced to shallow angle. The adiabatic film effectiveness shows a sharp drop in the region of $0 \leq x/D \leq 5$ due to the formation of 'neck' a region in which the coolant supplied is low. Thus, causing a drop of centre-line adiabatic effectiveness.

The film effectiveness is greater at low blowing ratio of M=0.5 as the overall film cooling effectiveness is greater with the increase of x/D, further down the streamwise distance compared to result with other blowing ratios. On the other hand, at blowing ratio of M=1.0, the overall film cooling effectiveness is the least effective with the increase of x/D, further down the streamwise distance. However, a different situation occurs for laterally average film cooling effectiveness because at high blowing ratio of M=2.0, the film effectiveness is greatest compared to other blowing ratio. For low blowing ratio of M=0.5, the film effectiveness is the least effectives compared to other blowing ratio.

The difference in results between the current study and past study might come from some error when conducting the experiment. There are some error that we managed to identify. First of all, the error might come when we are taking the reading and calculating the values of the mass flow rate. There might be some error when we are calibrating the reading. Besides that, the error might come from the thermocouple as some of the reading of the thermocouple are a bit off when they are calibrated together with the infrared thermography camera. This may be due to the fact that the thermocouples are not joint correctly when making they are made. Other than that, there heat loss at the piping of secondary flow is much greater than we anticipated. Thus, a large temperature difference between the temperatures just outside of the heater with the exit hole of the primary hole. Finally, the error might come from the secondary flow outlet. A flowmeter of either orifice meter or venture meter should be placed there instead of using a pitot tube. This is to minimise the volume of secondary flow that is lost greatly. Overall, the uses of injection angle of 30° improves the film cooling effectiveness.

V.   CONCLUSION

From this study, the results obtained shows that the application of sister holes at shallow angle of 30° increase the film cooling effectiveness especially at low blowing ratio. The results of the current study is compared with past research of Ely and Jubran [32] which utilises the addition of sister holes at 35°. From the comparison, the application of 30° sister hole has better film cooling effectiveness especially with the increase of spanwise distance at low blowing. Other than that, we found out that the usage of blowing ratio of M=1.0 and M1.5 is located between blowing ratio of M=0.5 and M=2.0 for both centre-line adiabatic effectiveness and laterally average film cooling effectiveness.

From the image taken using infrared thermography camera via FLIR QuickReport software, the data for temperature distribution of film cooling with sister hole configuration for all blowing ratios are able to be analyse. The importance of those images are essential for us to observe the intensity and the spanwise distance of thermal distribution. By far, sister hole is a great cooling technique as the film cooling layer can cover a great distance to cool the aerofoil or turbine blade. Therefore, from the result of this study shows that the blowing ratio of M=0.5 is effective for centre-line adiabatic effectiveness whereas the blowing ratio of M=2.0 is effective for laterally averaged effectiveness. However, by far the blowing ratio of M=0.5 has a better overall film cooling effectiveness.

ACKNOWLEDGEMENT

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