EXPERIMENTAL INVESTIGATIONS ON AERO-THERMAL INTERACTION OF FILM COOLING AIRS EJECTED FROM MULTIPLE HOLES: SHALLOW HOLE ANGLE

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ABSTRACT  
This paper presents thermal and aerodynamics investigations of multiple cooling holes with shallow hole angle. Three test models have been considered namely TMA, TMB and TMG. TMB is acting as the baseline test model having 35° hole angle cooling holes. The other two test models; TMA and TMG, have a shallow hole angle of 20° with different lateral pitch distance of 6D and 3D respectively. Total of twenty conventional cylindrical cooling holes have been arranged to form a five times four matrix. All three test models have been considered in the thermal investigations with only the shallow hole angle test models have been considered for the aerodynamics investigation. The film cooling effectiveness has been measured by means of infrared thermography while 3D-LDV has been utilized for the flowfield measurements. The measurements were carried out at single Reynolds number base on the hole diameter of 6200 at three different blowing ratios of 0.5, 1.0 and 2.0. All three blowing ratios have been considered in the thermal investigations with only the latter two blowing ratios were considered in the aerodynamics investigation. The results are presented in the form of contour plot of various variables including film cooling effectiveness, normalized u, v and w velocities, normalized root mean square of u velocity and Reynolds stress tensors. Distribution of laterally average film cooling effectiveness along the x-axis are also presented, showing that the 20° hole angle cooling holes provide a very promising results particularly at high blowing ratio. The velocities contours clearly capture the flow structure of the film cooling jets, along with the effects of blowing ratios and lateral pitch on the flowfield.

INTRODUCTION  
Thermal efficiency of a gas turbine can be unswervingly improved by means of higher turbine inlet temperature (TIT). Most of the modern gas turbines are now operating with the TIT in the range of 1800K to 2000K, which far surpasses the melting temperature of the turbine components material. Sophisticated cooling scheme is required to help protecting the turbine components from thermal failure. Review on turbine cooling technologies has been well described by Han et al. [1] with film cooling is one of available option. Film cooling intended to protect the turbine components surface from having a direct contact with the hot gases by the injection of the coolant fluid through the blade surface into the external boundary layer. The injected cold air will form a buffer layer of relatively cool air between the surface and the hot gases contained within the turbine flow path. Latest reviews on the film cooling technology developments have been made by Bunker [2] covering almost of all the available technologies on film cooling. The paper also includes suggestion on the future direction of the film cooling technologies.

Enormous numbers of experimental investigations dealing with both the aerodynamics and the thermal aspect of film cooling have been made available ever since and only a brief review will be provided in this paper. General review on flat plate surface film cooling studies prior to 1971 has been given by Goldstein [3]. Presented in the paper were the effects of various hole geometries and flow parameters that dictate the film cooling performance summarized from the prior available literatures [4–6]. Among the highlight of the paper are the superiority of inclined and shaped film cooling holes compared to perpendicular holes which contributes to momentum reduction at the hole exit due to wider exit area in inclined and shaped cooling hole which allows more coolant to remain attached to the surface, leading to better the film cooling effectiveness with the shaped cooling hole also help to laterally diffuse the coolant to provide better lateral film cooling coverage. The same observation has been made by other researchers with further reduction on the hole angle expected to produce better film cooling performance. Although the advantages of the shaped holes is acknowledged, significant number of studies still focuses on cylindrical holes particularly on the hole geometry properties including compound angle [7–10] and hole length to diameter ratio [11, 12]. Jubran and Brown [13] and Ligrani et al. [8, 9] presented film cooling
effectiveness of a multiple row cooling holes at different arrangement patterns. It was concluded that the two row cooling holes can significantly increase the laterally average cooling effectiveness either arranged in-line or staggered with the latter producing superior results. In the in-line arrangement, superposition effects result in better film cooling effectiveness downstream of the second row holes and beyond. Meanwhile, wider film cooling coverage downstream of the second row in staggered hole arrangement led to the same consequences.

In addition to the hole geometries and arrangements, the amount of injected air through the cooling hole is also an important variable that decides the film cooling performance which is determined by blowing ratio. Considerable amount of investigations have been done to clarify the effects of blowing ratio to film cooling performance. To name one of the latest relevant studies is Rabekah et al. [14]. The paper presented the effect of various blowing ratio to the film cooling performance with the wall temperature data obtained by using temperature and pressure sensitive paints. The study shows the film cooling effectiveness is significantly influenced by the blowing ratio which generally agreed with the previous available findings [4, 5]. Base on the available observations and interpretations, film cooling performance of a given hole geometry, arrangement and flow condition are closely related to the flow structure of a given case, therefore investigation on the flow structure in the film cooling system is imperative.

The aerodynamics investigations of film cooling had started as early as 1980’s with most of measurements were made by using the hot wire probe. It is found that phenomena such kidney vortices and flow separation plays a key role in film cooling performance. The kidney vortices as the prominent flow structure downstream of film cooling hole have been identified empirically by previous research [17–19], which concluded that the pair vortices entrain the mainstream fluid and transport it towards the blade surface. Recently, laser base measurement instruments namely Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) have been utilized to capture flowfield as presented in the work of Thole et al. [20]. The paper presents the investigation on the flowfield of expanded exit cooling hole with comparison to the conventional cylindrical hole. Prediction on the film cooling performance have been made base on the interpretation of the measured flowfield. Film cooling performance of similar hole geometries have been published later by Gritsch et al. [21]. Good physical insight has been established between the aerodynamics [20] and thermal results [21]. Thole et al. [20] also highlighted the importance of understanding the inside hole flowfield as the hole exit flowfield is expected to play a major role on the formation of the downstream hole flowfield.

Wright et al. [22] on the other hand have presented the effect of mainstream turbulent level to the film cooling flow structure. The flow structure have been measured by using PIV on the plane normal to lateral direction to reflect the previous thermal study using the identical hole geometry. It was concluded that the main reason behind poorer film cooling performance at higher turbulent level is due to the enhancement of the mixing between the coolant and the mainstream air which lead to coolant temperature drop thus reducing its cooling capacity. Kampe et al. [23] presented a complete study of diffuser shape film cooling holes covering both the thermal and the aerodynamics aspects. The thermal measurements have been made by IR camera while both PIV and LDV have been used in the aerodynamics measurements. The paper also presented a CFD results of the considered experimental condition. Physical interpretations on the film cooling performance have been made based on the aerodynamics results and a good agreement between the experimental and the CFD have also been achieved at the same time. The paper provides inclusive reviews of the diffuser shape film cooling holes.

This paper, likewise in the efforts by Kampe et al. [23], aims at the clarification of detailed velocity field associated with cooling holes using 3D-LDV and their characteristics in film effectiveness on the wall measured by IR camera. This paper especially deals with multiple cooling holes with two types of in-line configurations. As mentioned above, there are several preceding studies on the in-line hole configuration, which is usually for full coverage film cooling of combustor liners or turbine vanes. However, relatively few studies have been made on the in-line configuration in comparison with the staggered configuration because the former is believed to perform less than the latter. Nevertheless, the authors think it still worthwhile to investigate in-line configuration of multiple cooling holes with some updated ideas in order to expand the design space of cooling technologies. For this purpose, this study adopts very shallow hole angle, 20 degree. Besides, the in-line configuration is found to be beneficial when it comes to a comparison between the experiment and numerical simulation because the periodic boundary condition in the cross-flow direction is easily implemented in a numerical simulation compared to the case of staggered configuration. This feature eventually enables the authors to accomplish large-scale numerical simulation of the flow field including the effects of multiple cooling holes with less computational costs and the results will be reported in a near future.

**EXPERIMENTAL SETUP**

The experiments discussed in this paper involve two different experimental setups at Iwate University, Japan with each for the thermal and aerodynamic measurements. As both of these setups involved two different wind tunnels, two different experimental setups have been constructed. To make these thermal and aerodynamics results complementary to each other, the test model have been designed to have the same non-dimensional configuration, which will be further discussed in the next section. Experiments were conducted at targeted Reynolds number base on the hole diameter, \( \text{Re}_D = 6200 \) at three different blowing ratio, \( \text{BR} = 0.5, 1.0 \) and 2.0 for the thermal and only the latter two BR have been considered for the aerodynamics experiments. Details of the experimental condition are given in Table 1.

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Table 1: Details on the experimental conditions

<table>
<thead>
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<th>Test Model</th>
<th>Thermal</th>
<th>Aero</th>
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Figure 1: Details of the test model

Test model:

Three test models have been considered in this paper namely Test Model A, Test Model B and Test Model G. All test models were considered in thermal investigations and only the latter two test models were considered for aerodynamics investigations. For the purpose of simplification, the considered test models will be referred to as TMA, TMB, and TMG respectively later on this paper. All test models have twenty cooling holes arranged in five times four matrix as shown in Figure 1. The figure also shows the common non-dimensional configuration of the hole for both, thermal and aerodynamics studies. The cooling hole applied was a conventional cylindrical hole with inclination to the main flow direction at angle, $\theta = 35^\circ$ for TMB while TMA and TMG having $\theta = 20^\circ$. The cooling hole is separated in lateral direction at 6D distance for TMA and TMB while at 3D distance for TMG. The hole diameters for the thermal and aerodynamics studies are set to be at 7mm and 10mm, respectively. The thickness of the test plate was designed to provide the hole length to diameter ratio, $l/D = 6$. The test models were made from acrylic plate with the manufacturing precision of $\pm 0.1mm$. The inner surface of the test models were coated with black paint to emulate a black body in the thermal measurements and to reduce the surrounding noise during the aerodynamics measurements caused by laser reflection.

Thermal investigation:

Figure 2 shows the experimental setup for thermal investigation involved in the present study. The facility consists of a wind tunnel used to supply the mainstream air with separate blower to for the secondary air. The test duct cross section was designed to have 450mm width and 280mm height with a sharp upstream edge to recreate the boundary layer inside the test section. The test models were made from acrylic plate with thermal conductivity of 0.19 W.m$^{-1}$K$^{-1}$ with the cooling hole diameter of 7mm. Insulation layer made by styro-foam have been fix at the back of the test model to avoid heat conduction from secondary air chamber to the test model. The measurement window for the infrared camera measurement were made of 0.2mm thickness stretched polyurethane sheet to provide a transparent layer of infrared wave that was emitted by the test plate during the measurement. The use of such materials as the measurement window has been presented by Ekkad et al. [24]. Similar to the previous studies [24], thermocouple was placed on the test model to provide temperature data for the calibration purpose which was used to estimate the emissivity of the test surface. More details discussion on the thermography technique can be found in Tropea et al. [25] and Sargent et al. [26]. Location of the IR camera and the measurement window involved in the experimental setup is shown in Figure 2. During the measurements the secondary air was set to have the temperature at 20K higher than the main stream temperature. The IR camera engaged was a NEC/Avio H2640 with maximum recording capability of 30 frames per second with the measurement last for three minutes. The camera is operating in a long-wavelength infrared band with spectral range from 8 to 13\(\mu\)m.

Figure 2: The thermal experimental setup
The performance of a film cooling technique was evaluated by means of adiabatic film cooling effectiveness as been given by Eq. (1).

\[ \eta = \frac{T_w - T_{\infty}}{T_c - T_{\infty}} \]  

\( T_w, T_{\infty} \) and \( T_c \) are wall temperature, mainstream temperature and secondary air temperature respectively. \( T_w \) and \( T_c \) were measured by thermocouples during the measurement while the wall temperature, \( T_{\infty} \) was measured by infrared camera. Thermocouple has been placed on the wall surface to provide the actual surface temperatures during the measurements period. These temperatures are used to determine the temperature correction factor for each frame of the wall temperature captured by the infrared camera [25]. The corrected temperature is use to determine the film cooling effectiveness. The measurement lasted for three minutes to enable steady state analyses of film cooling effectiveness.

**Aerodynamics investigation:**

The aerodynamics investigations presented in this paper have been done in large-scale close-loop wind tunnel at Iwate University, Japan. The mainstream air was supplied to the test duct via flow straighteners, contraction nozzle and transition duct. The test duct size at 620mm x 260mm inlet dimension with 1550mm length. The inlet turbulent intensity of the experimental setup was determine by hot wire measurement at 0.59% with the boundary layer thickness approaching first film cooling row at \( y/D = 1 \). The view of the test duct together with the position of the laser probe involved in the measurement is shown in Figure 3. The secondary air was supplied through a separate blower equipped with a laminar flow meter. After passing the laminar flow meter, the secondary air will entered a secondary air chamber before being introduced into the mainstream flow through the cooling hole.

A three-component Laser Doppler Velocimeter (LDV) with coincident measurement method was used to capture the velocity fields. The LDV system engaged includes 85mm fiber optic probe, Dantec’s BS F60 Processor and 3-D Traversing System supply by Dantec. The probes were set to be inclined at 25° towards each other as shown in Figure 3. As the result of the alignment, the measured velocities need to go through a transformation process to represent the velocity components of the actual experimental axis which is done through the BSA Flow Software. Both the mainstream and the secondary air were seeded with particles produced by the SAFEX Fog Generator with average droplet size diameter of 1.545\( \mu \)m. A fog tank was used to enable continuous supply of the fog during the experiments. The uniformity of the seeding particle distribution was ensured through the data rate distribution on the measurement plane during the preliminary measurement. The plane size was also decided base on the preliminary measurement results with intention of avoiding insignificant area to be involved in the actual measurement. The numbers of counts involved during the measurement was set to be minimum at 750 counts, while almost all the considered measurement points recorded the counts value above 1000 counts. The measurement grid size applied on the plane was set to be at 2mm times 2mm which been proved to be small enough to capture the flow details through the preliminary measurement. Four measurement plane have been considered at \( x/D = 07, 17, 27 \) and 37 as been shown in Figure 4.

\[ \overline{u'v'} = \frac{1}{N} \sum_{i=1}^{N} (u_i - \overline{u})(v_i - \overline{v}) \]  

(2)

\[ \overline{u'w'} = \frac{1}{N} \sum_{i=1}^{N} (u_i - \overline{u})(w_i - \overline{w}) \]  

(3)
Measurement uncertainties:
The mainstream temperature uncertainty of the thermal measurement was recorded to be at 0.25% or ±2.1K with the secondary air temperature uncertainty recorded to be at 0.17% equivalent to ±1K. The wall temperature is recorded by the IR camera with the uncertainty of 0.38% equivalent to ±2K. Base on Moffat et. al. [27], the film cooling effectiveness uncertainty is predicted at 10%.

For the aerodynamics measurements, the measurement uncertainties are mainly on the LDV velocity measurement itself. Based on 95% confidence interval, the uncertainty of the freestream velocity is calculated to be at 1.4%, while the maximum velocity uncertainty inside the shear layer is recorded to be at 5.6%. Elsewhere, the positioning uncertainty of the LDV probe volume with respect to the hole position for all axis were at Δx = ±0.01 mm, Δy = ±0.01 mm and Δz = ±0.01 mm.

RESULTS AND DISCUSSION

The results presentation and discussion of the present study are separated into the thermal aspect and aerodynamics sections. In the thermal section, verification of the current thermal setup and procedure is made with comparison to previous results. Contour plot of film cooling effectiveness are presented together with the laterally average film cooling effectiveness distribution along the x/D distance. As for the aerodynamics results, contour plots for variables including normalize velocity component of u, v, and w, normalize u-RMS and normalize Reynolds stress tensor of ∇u and ∇w are presented. The normalize variables have one single reference value which is the main stream velocity for the associated cases. Although the results and discussion will be presented in two different sections, the discussion engages some correlations between the two sections as the author aim to build the connection between the thermal and the aerodynamics results.

A laterally averaged film cooling effectiveness measured by the present study: TMB; BR 0.5 and TMA; BR 0.5 together with the previous studies of Kohli et al. [28] and Sinha et al. [16] with the laterally averaged film cooling effectiveness covers from z/D = -1.5 to 1.5. Measured film cooling effectiveness in the present study of TMB compares favorably to the previous literature [16, 25]. Larger discrepancy found at x/D = 6 onwards can be explained by the existent of the second row cooling hole at x/D = 10 which slowing down the decay of the film cooling effectiveness coverage downstream of the hole. Better film cooling effectiveness of TMA between 0.8 < x/D < 3.0 can be observed from the graph. This is contributed by several factors associated to TMA configuration; a) distribution of the exiting jet momentum and, b) better lateral spread of the secondary air. These two factors will be discussed further in the next section.

Figure 6 shows the film cooling effectiveness contour plot of TMB at all blowing ratios. At BR = 0.5, the figure clearly shows the growth of the film cooling coverage along the x-axis direction. Physical interpretation of such growth is due to the in-line hole arrangement employed in the present study causing the superposition effects to take place downstream of the second row cooling hole onwards. As the secondary air of the upstream row is not yet totally dissipated into the mainstream air, these airs will be combining with the newly introduced secondary air from the downstream rows, thus having greater cooling capability. The same observation and interpretation of the superposition effects were made by the previous researchers [7-9, 13]. The bottle neck shape of the film cooling effectiveness observed just downstream of cooling holes confirms the separation and reattachment of the secondary air from and to the wall cause by the exiting jet. One should notice that such phenomenon has become indistinct from the second row onwards which could also be explained by the superposition effect discussed earlier. Although the superposition effect hinted to produce a better film cooling effectiveness particularly further downstream of the second row, such observabel fact can only be applied at relatively low blowing ratio for the case of TMB as been shown in Figure 6 for BR = 1.0 and 2.0. In TMB, the superposition effects can still be observed at BR = 1.0 but cannot be observed in the case of BR = 2.0.

Figure 7 shows the film cooling effectiveness contour of TMA at BR = 0.5, 1.0 and 2.0. Similar to the case of TMB, the overall film cooling effectiveness distribution was found to be highest at BR = 0.5 compared to the BR = 1.0 and 2.0 which have slander film cooling coverage downstream of the cooling holes. As the secondary air at a lower BR will have less exiting jet momentum compared to the higher BR, the secondary air capable to remain attached to the surface consequently producing a better film cooling coverage. Such phenomenon is well verified by the previous researches [14, 16–18]. Such phenomenon can also be confirmed by shorter film cooling effectiveness tails found at higher blowing ratio downstream of the fourth row (x/D > 30). In comparison between TMA and TMB, better film cooling coverage can be found in afore
mention test model at all blowing ratios as been shown in Figures 6 and 7. This can be further confirmed by the laterally average film cooling effectiveness of the two test models presented in Figure 8.

Figure 6: Film cooling effectiveness contour for TMB

Figure 8 shows the comparison of laterally averaged film cooling effectiveness between TMA and TMB along the $x/D$ distance. The presented average value covers one pitch distance of $-3.0 < z/D < 3.0$. Generally, the laterally average film cooling effectiveness value of TMA surpasses the value of TMB. Only at BR = 0.5, the performance of TMB a match to TMA with the latter mention test model performing much better at higher blowing ratios. Better performance of TMA even at higher blowing ratio is contributed by the shallow hole angle of TMA at $\theta = 20^\circ$. The shallow angle contributes to lesser penetration of the secondary air into the mainstream thus allowing more coolant to remain attached to the wall compared at the case of larger hole angle. In addition, the shallow angle in TMA also afford a wider hole exit area which will diminish the exiting jet momentum, lessen the lift-off effect of the secondary air while entering the mainstream flow. Figure 9 shows the film cooling effectiveness contours of TMG at BR = 0.5, 1.0 and 2.0. The effect of shorter pitch distance of TMG ($P_z = 3D$) can clearly observed from the figures.

In comparison to TMA (Figure 7), better film cooling coverage can be observed in TMG at all blowing ratios particularly after the second row ($x/D > 20$). The existent of neighboring hole which induces interaction between neighboring secondary air leads to better film cooling in between the hole. In addition, the existent of full film cooling coverage can be observed at BR = 2.0 downstream of the fourth row ($x/D > 30$). Figure 10 shows the comparison of laterally averaged film cooling effectiveness between TMA and TMG along the $x/D$ distance. The presented value is determine over one pitch distance for TMG of $-1.5 < z/D < 1.5$. In general, the laterally average film cooling effectiveness value of TMA and TMG match each other until the third row with TMG start to distinguish itself as a better performer further downstream ($x/D > 30$).

Figure 7: Film cooling effectiveness contour for TMA

Figure 8: Laterally averaged film cooling effectiveness of TMA and TMG

One should also be notified on the occurrence effect of the heat conduction between the neighboring holes. Shorter pitch distance between the holes in TMG enhancing the conduction heat transfer between the neighboring hole thus leading to error in the film cooling effectiveness prediction particularly at the hole vicinity. The heat conduction effect can also be observed in Figures 6, 7, and 9 represented with higher film cooling
effectiveness upstream of each row cooling hole. The heat conduction at the near hole region estimated to provide an error of 10% to the film cooling effectiveness predicted by the measurement.

![Figure 9: Film cooling effectiveness contour for TMG](image)

![Figure 10: Laterally averaged film cooling effectiveness of TMA and TMG](image)

**Aerodynamics aspect:**

Figures 11–14 show the normalized $u$-velocity for TMA and TMG at BR = 1.0 and 2.0. Inclusive in the figures are the vector plot of $v$ and $w$ velocity components. The vector plots confirm the existent of kidney vortices which is well documented as the prominent flow structure in film cooling application. At BR = 1.0, the blockage effect represented by high velocity region as suggested by previous research cannot be observed clearly in both TMA and TMG except at $x/D = 37$. At further upstream ($x/D = 07, 17, 27$), the secondary flow momentum by far dissipated into the mainstream flow thus disable any occurrence of the blockage effects at the mentioned locations. The existent of the blockage effects at $x/D = 37$ is an indication of the superposition effect due to the in-line hole arrangement considered in the present study. At BR = 2.0, the high velocity region can be spotted at $x/D = 0$. In addition to the blockage effects, the high velocity region at BR = 2.0 also contributed by the high velocity of the secondary flow exiting the cooling hole in comparison to the mainstream velocity. Similar indication of the existent of superposition effects can be observed. As the secondary flow introduced by the upstream hole is not yet totally dissipated into the mainstream flow, the newly injected secondary flow from the next row hole is merging with the upstream introduced secondary flow, producing more intense high shear layer represented by the high velocity region as shown in Figures 11–14. Thus, associated with the discussion of Figure 10 in the thermal investigation section, the superposition effects enhance the film cooling effectiveness of TMA and TMG at $x/D > 10$.

Figures 12 and 14 show that the lift-off effect is greater at higher BR compare to low BR cases shown in Figures 11 and 13. Higher jet exit momentum at higher BR causes the jet to penetrate more into the main flow compared to lower BR, thus enhancing the formation of the kidney vortices which associated with the lift-off effects. In comparison between TMA and TMG, high shear layer associated by the high velocity region in TMG at BR = 2.0 is wider in the lateral direction and closer to the wall. Laterally wider high shear layer region indicates better lateral spread of the secondary flow in TMG compare to TMA which enhance the film cooling performance as been discussed in the thermal investigation section on Figures 9 and 10. The high shear layer region which is nearer to the wall in TMG also indicates a weaker lift-off effect which will also benefit the film cooling performance. One of the physical interpretations of this laid on the existent of neighboring hole which is closer in TMG with lateral pitch distance of $P_z = 3D$ compared to $P_z = 6D$ in TMA. The neighboring holes will generate similar flow structure consisting kidney vortices which will grow further downstream after the hole exit. At some distance, the size of these vortices will be wide enough to induce interaction with other vortices created by the neighboring holes. The interaction can be observed from the vector plot presented in Figures 13 and 14. This interaction tends to weaken the lift-off effects of the secondary air which help to give better lateral spread of the secondary air.

The above explanation is supported by the results of normalized $v$-velocity as shown in Figures 15–18. At a given blowing ratio, the only possible way to have better lateral spread of the secondary air is by having less penetration of the secondary air into the main flow. Such phenomena are shown in Figures 15–18 where the magnitude of the positive velocity region in Figures 15 and 14 is higher to the one in Figures 17 and 18 correspondingly. The figures indicate a lower value of positive velocity region in TMG compared to TMA particularly at BR = 2.0. The significant reduction of the
positive velocity region at higher BR also confirms the interpretation that the interaction between the neighboring kidney vortices caused a better spread of the secondary air. At a higher BR ratio, the interaction between the neighboring vortices could happen at shorter $x/D$ distance than in the lower BR cases. Thus, larger difference of $v$-velocity between TMA and TMG has been found at higher BR. Figures 16–17 also confirm the interaction between the neighboring kidney vortices shown by the negative velocity region in TMG having a greater magnitude compared to the TMA. Physically, at the outer boundary, both of the neighboring vortices have the same flow direction thus serving to a high velocity in the discussed region towards the wall. The upward flow movement found in Figures 15–18 have the same growth pattern, where at $x/D = 37$, the measured upward velocity magnitude is lower compared to the one found at $x/D = 27$. This should clarify the existent of the blockage effect of the downstream cooling hole which promotes the upward movement in the flowfield downstream of each corresponding upstream hole. At $x/D = 07$, 17 and 27, the upward flow movement is contributed by three matters; the secondary air, the lift-off movement of kidney vortices and the blockage effect of the secondary flow introduction from downstream cooling holes. As for the case at $x/D = 37$, only the first two matters took effects resulting lower magnitude of upward movement as shown by Figure 15–18.

Figures 19–22 show the normalized $w$-velocity results. The results could be used to explained the benefit of neighboring vortices interaction which occurs in TMG. The $w$-velocity magnitude found in TMG shown by Figures 20 and 21 are lower compared to the one in Figure 18 and 20 of TMA. This indicates the interaction between the neighboring vortices is dampening the kidney vortices growth in TMG with the difference in the magnitude can clearly be observed at both blowing ratios. The vortex dampening is cause by unordinary movement of the flowfield induces by the neighboring holes vortices interaction. The vector plots in the region mark by the red circle in Figures 21 and 22 show that instead of creating a circular movement forming the vortices, some of the vortical flow were withdrawn into the neighboring hole vortex circle thus weaken the vortices strength. As some of the vortical momentum has been withdrawn from the vortices, it causes the size and the growth rate of the vortices to be stunted.

Figures 23–26 show the normalized $u$-$RMS$ for TMA and TMG at BR = 1.0 and 2.0. The value of $u$-$RMS$ normalized to the mainstream flow velocity which also known as turbulent level, $Tu$ given in percentage. High $Tu$ region can be interpreted as a region of strong interaction between the mainstream flow and the secondary air. The peak $Tu$ value for TMA recorded to be at 28% while only at 11% for TMG at BR = 2.0. Similar to the findings of Thole et al. [20], the high $Tu$ region is found to be a just beneath of the high normalized $u$-velocity region shown in Figures 11–14. The merging of the medium level of $Tu$ region which can be found in Figures 25 and 26 are another clear evident of the occurrence of interaction between the vortices generated by the neighboring hole.
Figure 13: Normalize $u$-velocity for TMG at $BR = 1.0$

Figure 14: Normalize $u$-velocity for TMG at $BR = 2.0$

Figure 15: Normalize $v$-velocity for TMA at $BR = 1.0$

Figure 16: Normalize $v$-velocity for TMA at $BR = 2.0$
Figure 17: Normalized $v$-velocity for TMG at $BR = 1.0$

Figure 18: Normalized $v$-velocity for TMG at $BR = 2.0$

Figure 19: Normalized $w$-velocity for TMA at $BR = 1.0$

Figure 20: Normalized $w$-velocity for TMA at $BR = 2.0$
Figure 21: Normalize $w$-velocity for TMG at BR = 1.0

Figure 22: Normalize $w$-velocity for TMG at BR = 2.0

Figure 23: Normalize $u$-RMS for TMA at BR = 1.0

Figure 24: Normalize $u$-RMS for TMA at BR = 2.0
Figure 25: Normalize $u$-RMS for TMG at BR = 1.0

Figure 26: Normalize $u$-RMS for TMG at BR = 2.0

Figure 27: Normalize $\overline{u'v'}$ for TMA at BR = 2.0

Figure 28: Normalize $\overline{u'v'}$ for TMA at BR = 2.0
Figures 27 and 28 show the Reynolds stress tensor of normalized $\overline{u'w'}$ for TMA and TMG at $BR = 2.0$ respectively. Two main regions in the normalized $\overline{u'w'}$ plots can be observed; negative and positive regions which can be confirmed by the finding of previous researches [20, 22]. Both of the regions are proof of existent of high shear region which indicates the interaction between the flow and the wall (negative region) also between the mainstream and the secondary air (positive region). Reynolds stress tensor of normalized $\overline{u'w'}$ contour plots are presented in Figures 29–30. Similar to the explanation of normalized $\overline{u'v'}$, the regions existent can represent the boundary in which there are significant flow interaction which in this case is between the mainstream flow and the secondary air. The region of high $\overline{u'v'}$ and $\overline{u'w'}$ also represent the region of high turbulent eddies production in the flowfield.

CONCLUSION

Thermal and aerodynamics investigation of multiple cooling holes have been presented. Three test models have been considered namely TMA ($\theta = 20^\circ$; $P_z = 6D$), TMB ($\theta = 35^\circ$; $P_z = 6D$) and TMG ($\theta = 20^\circ$; $P_z = 3D$). Experiments were carried out at $Re_D = 6200$ involving $BR = 0.5$, 1.0 and 2.0 for thermal investigation and only the later two blowing ratios in the aerodynamics investigation. The following conclusion can be made from the presented study:-

1. Thermal and aerodynamics results confirmed the existence of the in-line hole arrangement superposition effects. The effects enhance the film cooling performance of TMA and TMG at all blowing ratios while only at $BR = 0.5$ for TMB.

2. Instead hindering the film cooling performance, higher blowing ratio provides better film cooling coverage for TMG at $x/D > 20$ due to the interaction between the neighboring kidney vortices.

3. The interaction between the neighboring vortices in TMG dampened the growth of the vortices through allowing some of the vortical momentum of the corresponding vortex to be withdrawn by the neighboring vortices thus weakens the strength and growth rate of the corresponding vortices.

4. The Reynolds stress tensor of $\overline{u'v'}$ and $\overline{u'w'}$ represent the high shear region created by the interaction between the mainstream, secondary flow, and wall. The region of high $\overline{u'v'}$ and $\overline{u'w'}$ also represent the region of high turbulent eddies production in the flowfield.

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