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Experimental and Numerical Investigation on Flowfield of Film Cooling from Multiple Holes

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Abstract. This paper presents the experimental and numerical investigation on flowfield of multiple film cooling hole focuses on shallow hole angle at 20°. An in-line hole configuration consist of 20 cooling holes have been considered in the present study. Investigation have been carried out at Re_D=6,200 and BR=1.0 with the experimental investigation involves 3D-LDV device to capture the experimental velocity flowfield. The numerical investigation was carried out through RANS analyses with the employment of shear stress transport turbulent model. The results highlights the benefit of shallow hole angle configuration with good agreements have been achieved between the experimental and the numerical results.

Introduction

Film cooling is achieved by injecting coolant fluid through the blade surface to perform a layer protecting the surface to have direct contact with the hot gases. The technology has been the primary focus of turbine blade cooling research for the past half century. Enormous researches have been carried out to better film cooling technology which has been well described by Han et al. [1] and Bunker [2]. Endless alternation base on the conventional film cooling can be made to improve film cooling effectiveness. Ligrani et al. [3] have shown that further reduction on the hole angle is expected to produce better film cooling performance. The common hole angle available in the literature is at 35° which is limited by manufacturing difficulties of shallower hole angle. The huge design space available for cooling hole configuration made computational fluid dynamics (CFD) as one of the favorite tools to enhance the film cooling technologies exploration instead of the empirical approaches. To name few related researches involving CFD are Ely et al. [4] and Kusterer et al. [5]. Both of these works [4, 5] utilizing CFD to evaluate the film cooling performance of potential holes configurations; sister holes and NEKOMIMI hole respectively. Although CFD unarguably convenient, its capability to predict highly unsteady flowfield involved in film cooling is still in doubt, particularly in the employment of Reynolds Average Navier- Stokes (RANS). The availability of more complete experimental flowfield results as presented by Wright et al. [6], Kampe et al. [7], and Kamil et al. [8] create the opportunity for better CFD evaluation. The present study aims to compare the flowfield of typical cooling hole angle at 35° with the shallower holes angle at 20°. Include together in the present paper is the flowfield comparison between experimental and the CFD.

Experiments

A three-component Laser Doppler Velocimeter (LDV) with coincident measurement method was used to capture the velocity fields. The LDV system includes 85mm fiber optic probe, Dantec's BS F60 Processor and 3-D Traversing System provided by Dantec. The seeding particles in used were produce by SAFEX fog generator with the mean diameter of 1.545μm. Fig.1 shows the test duct together with laser probe positioning involved in the measurement. Details of the experimental setup have been described in Kamil et al. [8]. In the present study, the velocities data were measured at four YZ planes located at, x/D=03, 13, 23 and 33. Two test models have been considered namely TMA and

TMB. The test models consist of 20 cooling holes arranged to perform 5 times 4 matrix as shown in Fig. 2. The cooling hole applied was a normal cylindrical hole with inclination angle, $\theta = 20^{\circ}$ and 35° for TMA and TMB respectively. The hole diameter was set at 10mm with the thickness of the test plate designed to provide the hole length to diameter ratio, l/D=6. The measurement surface of the test models was coated with black paint to reduce the surrounding noise during the measurement caused by laser reflection. Experiments have been done at targeted Reynolds number based on the hole diameter, $Re_D = 6200$ at single blowing ratio, BR = 1.0.

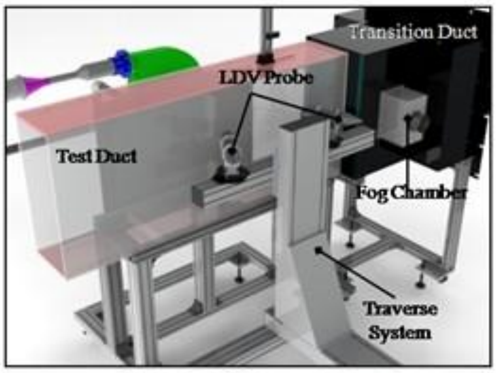

Fig. 1: Experimental setup

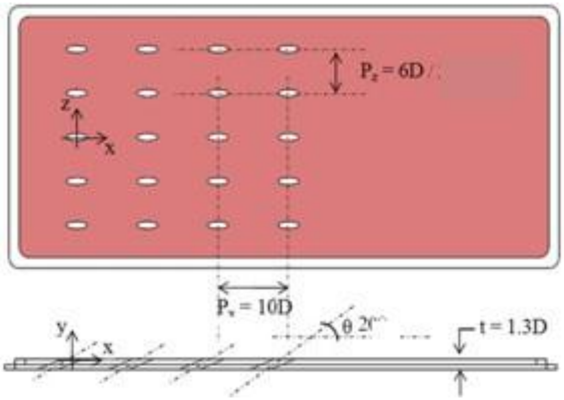

Fig. 2: Hole arrangments

CFD

Computational fluid dynamics investigation of the present study were carried out by ANSYS CFX ver. 12 involving RANS analyses with the employment of shear stress transport (SST) turbulent model. Fig. 3 shows the details of the CFD model considered in the present study with all the boundary conditions value were adapted from the experimental conditions. The mesh involved is unstructured meshes generated through ANSYS ICEM CFD ver. 12. Mesh dependency test has been carried out with the final mesh configuration of TMA and TMB consists of approximately 12 million elements with prism layers were applied at the near wall region. The first node distance from the wall set to meet y^{+} value of unity at 0.001mm. Modification have been made on the inlet boundary area of the test model to reproduce the approaching velocity profile captured during the experiments with relatively high boundary layer thickness at 10mm.

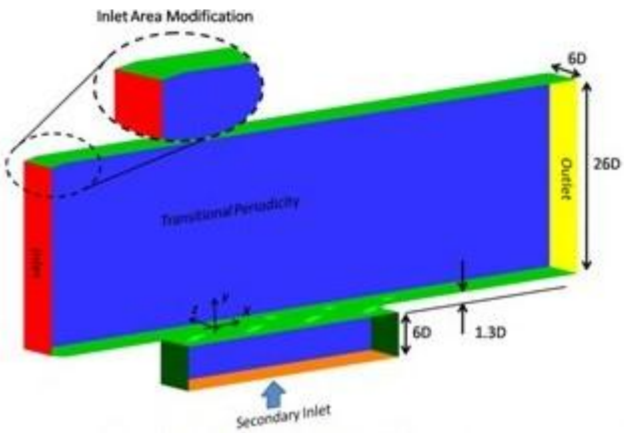

Fig. 3: Details of CFD domain

Results and Discussion

The presents study involves a typical hole angle configuration with $\theta = 35^{\circ}$ acting as a base line test model for comparison to shallow hole angle configuration with $\theta = 20^{\circ}$. As a start, discussion will be made on the flow structure of in-line multiple film cooling hole of TMB. The discussion on the flow structure will be extended with the comparison between the flow structure of TMA and TMB. The discussions include all three normalized velocity components u, v, and w which are presented in contour plots. The normalization of the velocity components have been made base on the mainstream velocity of each respective case. The discussions will be continued with the comparison between the experimental and the CFD results. Base on the CFD results, discussion on inside hole flow structure will also be included

Figure 4(a), 4(b) and 4(c) show the contour plot of normalized *u*, *v* and *w* velocity components respectively of TMB. Embedded together within the figure are 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. The introduction of the secondary air obstructing the mainstream flow generates the blockage effects represented by a high *u* velocity region as been shown in Figure 4(a) at *x*/D = 23 and 33. The blockage effects cannot be clearly seen at *x*/D = 03 and 13 suggest that the secondary air momentum introduced by the first and second row cooling holes by far dissipated into the mainstream flow. The occurrence of low velocity region at the center of *x*/D ≥ 13 planes indicates the existent of superposition effects provided by the present in-line holes arrangement. These regions are generated by the interaction between the upstream secondary air and the mainstream air thus leaving the approaching mainstream flow of the second row onwards at a lower magnitude. The regions proliferated further downstream at *x*/D ≥ 13 which should further offset the existent superposition effects of the in-line hole configuration. Fig. 4(b) also can be used to describe the superposition effects as been discussed earlier. The growth of high velocity region at *z*/D = 0 towards the downstream distance indicates higher penetration of the secondary air into the mainstream flow which is parallel to the discussion of Fig. 4(a). Meanwhile, the spread of the negative *v* velocity region towards the downstream measurement plane indicates the growth of the kidney vortices which will enhance the lift-off effect and subsequently hinder the film cooling performance. The growth of the kidney vortices at some point will induces the interaction between the neighboring vortices which have been describe in the work of Kamil et al. [8]. Fig. 4(c) clearly indicates the existence of the interaction between the neighboring hole at the mid lateral distance of *z*/D = -3.0 and 3.0. The interaction between the neighboring vortices could possibly dampen the kidney vortices growth with some of the vortical flow of the corresponding vortices were withdrawn into the neighboring hole vortex circle thus weaken the corresponding vortical momentum [8].

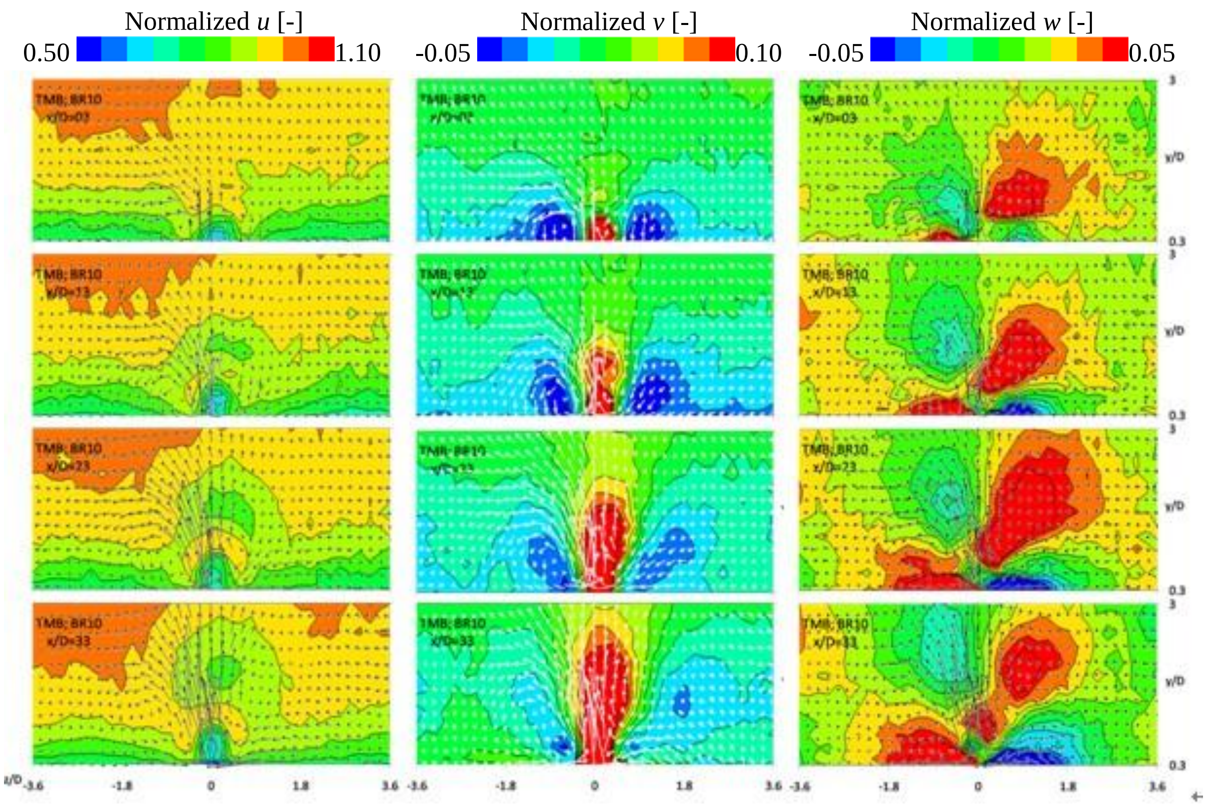

Fig. 4: Results of TMB; (a) Normalized u velocity, (b) Normalized v velocity, and (c) Normalized w velocity

Fig. 5(a), 5(b) and 5(c) show the flowfield contour plot of TMA at all measurement planes. In comparison with TMB, the blockage effects represented by high velocity region of normalized *u* can be observe at all measurement locations as be shown in Fig. 5(a). This could be explained by the exiting jet momentum distribution between the two different hole angle configuration of TMA and TMB. Having shallow angle at 20° in TMA, the occurrence of the flow separation inside the cooling hole is much more severe than the TMB case. As the hole upperstream wall region hold more secondary air, the exiting jet will not easily dissipated into the mainstream air thus enhance the blockage effects of TMA hole configuration. Shallower hole angle will also allow more exiting jet momentum to be distributed in the mainstream flow direction instead of the vertical direction thus enhancing the blockage effects. Fig. 4(b) and Fig. 5(b) can also be used to support the above physical interpretation with less penetration of the secondary air in TMA will allows more secondary air to remain attached to the surface thus better the film cooling performances. The interaction between the neighboring vortices that have been discussed on Fig. 4(c) cannot be observed clearly in Fig. 5(c). It could be suggested that the kidney vortices development rate in TMA is lower than the TMB which subsequently dampen the lift-off effects and the entrainment of the mainstream air towards the surface. The above discussed characteristics of TMA; inside hole flow separation, higher momentum distribution in the flow direction, lesser penetration of the secondary air, and lower development rate of the vortices will lead to a better film cooling effectiveness in comparison to TMB.

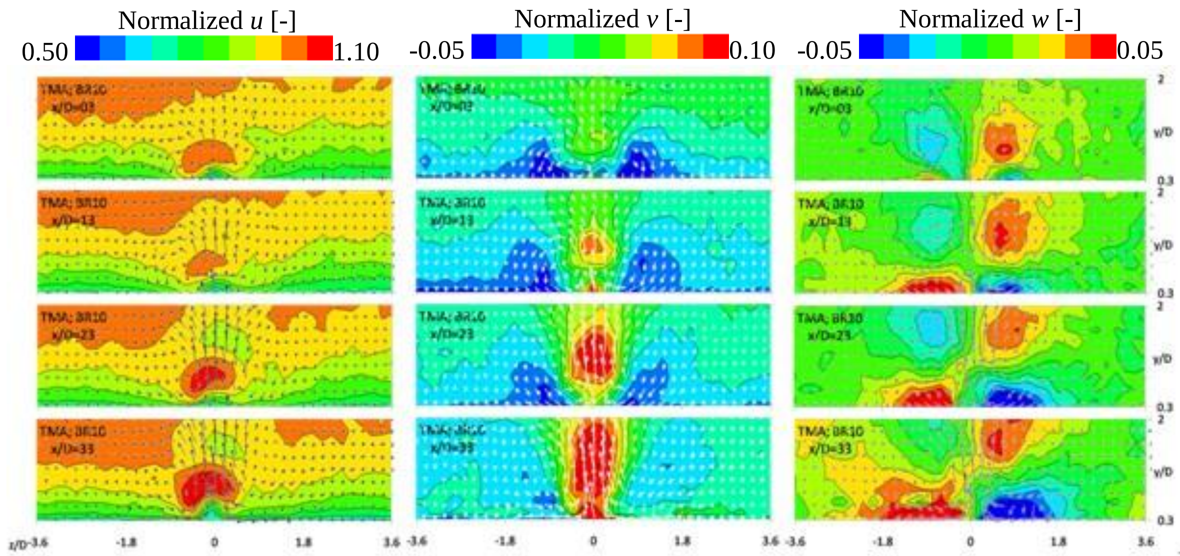

Fig. 5: Results of TMA; (a) Normalized u velocity, (b) Normalized v velocity, and (c) Normalized w velocity

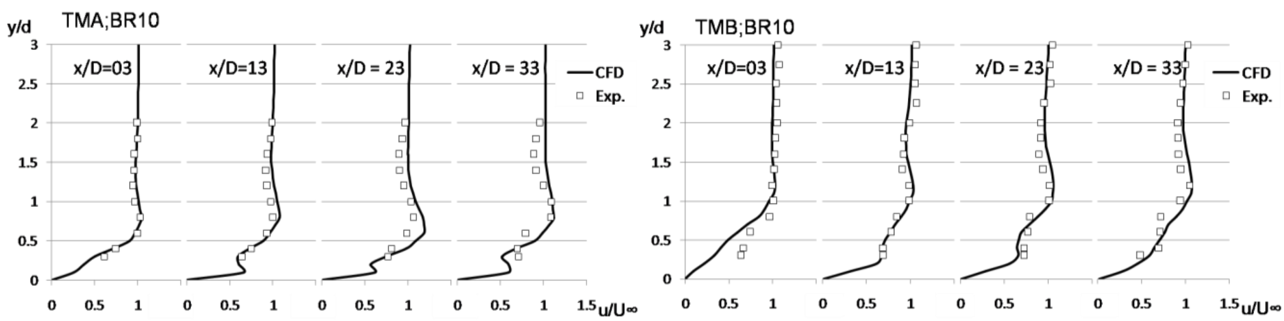

Fig. 6: Velocity profile comparison between the experiment and CFD

Fig. 6 shows the comparison between the experiments and the CFD velocity profile for TMA and TMB. The velocity profile is presented in terms of normalized *u* velocity with reference to the mainstream velocity of respective cases. In general, good agreements have been achieved between the experiments and the CFD results in both cases. It should be mention that such agreement had only been achieved after the authors have opted the modification of the inlet boundary area to reproduce the approaching velocity profile captured from the experiments. The negative velocity gradient observed in the figures indicates the blockage effects due to the introduction of the secondary flow into the mainstream flow which is more distinguish in TMA compared to the TMB. Given the good agreement, the CFD can be used to describe the flow phenomena at inaccessible region in the experiments; inside the cooling hole. Fig. 7 shows the inside hole absolute velocity contour and the vector plots for both cases of TMA and TMB. High velocity observed at the upstream wall region associated with the low velocity at the downstream region indicates the flow separation phenomenon due to the inclination of the cooling hole. Although not presented here, velocity profile on the presented plane is pointing out higher velocity at the upperstream wall region in TMA in comparison with TMB which represent the severity of the flow separation phenomenon at shallow hole angle of TMA. At the other end, the vector plots show the formation of the kidney vortices in TMB is already occurring inside of the cooling hole while there are no clear indications of such phenomenon occurring in TMA.

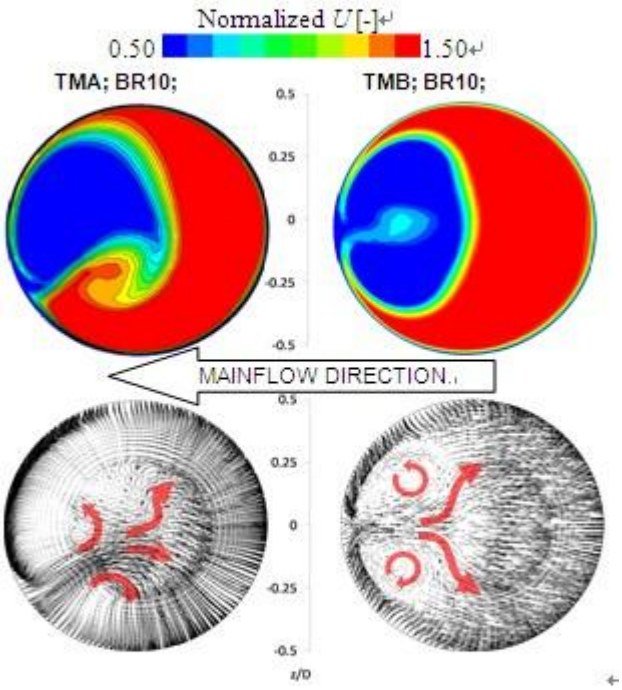

Fig. 7: Inside hole flowfield and vector plots

Summary

The paper focuses on the flowfield comparison between the typical hole at 35° configuration and shallower holes angle at 20° configuration. Experimental results of the flowfield have been presented with comparison to the CFD flowfield results. Kidney vortices as prominent flow structure in film cooling have been successfully captured in the present study together with the superposition effects due to the in-line hole arrangements. In addition, shallower hole angle enable more secondary flow to remain in the near wall region thus expected to produce better film cooling performance. Comparisons to the CFD results have also been presented and discussed with generally good agreement have been achieved. In addition, the CFD have also been used to describe the inside hole phenomena which is inaccessible through the experiments.

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