Experimental Study on Film Cooling Effectiveness of Shallow Hole with Upstream Sister Holes

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Abstract. This paper deals with effects of sister hole on cylindrical shape film cooling performance. The objective of introducing sister holes is aiming for further enhancement of film cooling effectiveness of conventional film cooling. The performance of sister holes, installed upstream of primary holes with shallow inclination angle 20°, is thoroughly investigated and reported in this study. Effects of blowing ratio (*M*) are examined. Three different blowing ratios, 1.0,1.5 and 2.0 are examined in this study to explore the capability of sister holes to suppressing the growth of counter-rotating vortex pair (CRVP) associated with the ejected cooling air, then enhancing the cooling air attachment to the flat plate surface. In order to investigate the film effectiveness, a steady-state method using a high-resolution infrared camera is adopted. Mainstream temperature and secondary air temperature is measured by K-type thermocouple. The result showed significant improvement compared to shallow hole of 35°. The optimum blowing ratio is 1.5. Smaller shallow angle and upstream sister holes reduce the jet lifting effect of the secondary air flow. Future study can be done on shallow hole of shallow angle and blowing ratio around 1.5 in order to further improve the film cooling effectiveness.

Introduction

Gas turbine, an internal combustion engine using air as working fluid, is widely used today in aircraft applications, power generation applications and other applications. According to Han et al. [1], in order to achieve a better performance in future, it is necessary to increase its thermal efficiency by increasing the turbine inlet temperature and also the compression ratio. Therefore, development of high-temperature material and highly sophisticated cooling scheme are essential. In study, the focus will be on the external turbine cooling, in other words, film cooling.

Goldstein [2] stated that film cooling is the introduction of a secondary fluid at one or more discrete locations along a surface exposed to a high temperature environment to protect that surface not only in the immediate region of injection but also in the downstream region. It is affected by few factors include pressure ratio and temperature ratio of coolant to mainstream, the location, configuration and distribution on the airfoil of the film cooling hole and the design of the film cooling holes.

Abdullah et al. [3] have done thermal and aerodynamics investigations of multiple cooling holes with shallow hole angle. A baseline test model, TMB is set up with 35° hole angle cooling holes. Another two models, TMA and TMG, have shallow hole angle of 20° with different lateral pitch distance of 6D and 3D respectively. For the test plate, 20 cooling holes arranged in 5x4 matrix. The experimental condition is Reynolds number of 6200 with blowing ratios of 0.5, 1.0 and 2.0. In-line hole arrangement superposition effect is detected from the studies which has increased the film cooling effectiveness of all test models at all blowing ratios. Only the film cooling effectiveness of TMB at blowing ratio of 0.5 is not increased. In other cases, higher blowing ratio usually reduces the film cooling performance. However, in this case, specifically for TMG, the film holes produce kidney vortices. The interactions provides a better film cooling coverage at *x/D*>20.

On the other hand, the study of Ely et al. [4] focused on a computational analysis on the effect of the sister hole control on film cooling from short holes. Short hole is a design of film cooling hole with the length to diameter ratio (*L/D*) equal or less than one. It is liable to create complicated vortex structures. One significant difference between short hole and long hole is the flow fields created. The study is to determine the best position of sister holes to maintain flow adhesion along the surface of the blade actively. From the study, with sister holes, the short hole produces similar form as long hole. The near hole film cooling effectiveness can be improved by using upstream sister holes while the downstream film cooling effectiveness can be improved by using downstream sister holes.

As for the current study, it aims to investigate the film cooling effectiveness of the film holes with shallow angle of 20° with upstream sister holes attached to the primary hole by using experimental method. with blowing ratios of *M*=1.0, 1.5 and 2.0.

Experimental Method

Experimental Setup. The detail of the hole geometry was depicted in Figure 1.This hole block consist of 5 cooling holes in one row. The primary hole diameter, D, was 8mm and the hole pitch was 4.5D. Sister holes diameter was 0.75D and the distance to primary hole was 0.75D.The inclination angle of the primary and sister holes was 20°. Figure 2 shows the schematic diagram of experimental work. Two air supply systems existed in the experimental facility, and the secondary air was heated. The secondary air entered the cooling holes plenum chamber from the bottom side of the chamber. The mainstream passed flow straighteners and the transition nozzle and flowed into the test section. The mainstream velocity was measured by a Pitot tube installed 100mm downstream of the test duct entrance. The flat plate test model was installed on the side of the test duct. The test model made of acrylic was installed on the mainstream side of the test duct. A rectangular window of thin layer plastic was mounted to the side plate opposite to the test model in order to measure the temperature of the test surface by a high-resolution infrared camera (FLIR).The temperature of the mainstream and secondary air was measured using K-type thermocouple.

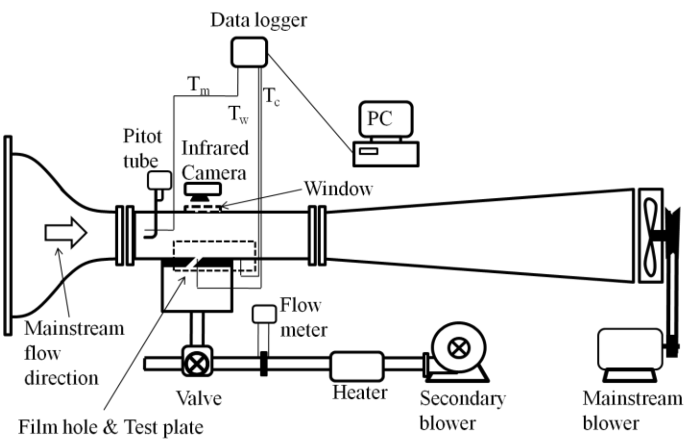

Fig. 1 Sketch of Experimental Setup

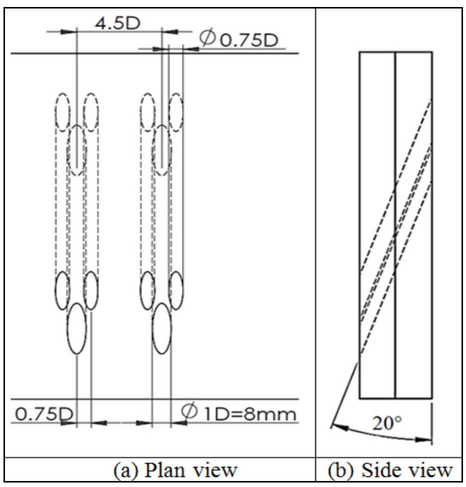

Fig. 2 Geometry of Shallow Hole with Upstream Sister Holes

Table 1 Test conditions

Mainstream			Secondary		M	DR
V_m(m/s)	T_m(K)	ρ_m(kg/m^3)	T_s(K)	ρ_s(kg/m^3)		
15	302	1.17	323	1.09	1	0.93
15	302	1.17	323	1.09	1.5	0.93
15	302	1.17	323	1.09	2	0.93

Test condition. All test were conducted in the open loop low speed wind tunnel at mainstream Reynolds number of 7143 based on primary cooling hole diameter (*D*). The flow velocity and temperature in the duct entrance were about 15 m/s and 303K, respectively. The blowing ratio BR, one of the most dominant parameter for film cooling is defined as

$$M = \frac{\rho_c V_c}{\rho_m V_m} \qquad (1)$$

where, ρ_c is density of secondary air, V_c is velocity of secondary air, ρ_m is density of mainstream air and V_m is velocity of mainstream air. Blowing ratios (*M*) examined were about 1.0,1.5 and 2.0. The density ratio (*DR*) were about 0.93.

Data analysis. Film effectiveness η is defined as

$$\eta = \frac{T_{aw} - T_m}{T_c - T_m} \qquad (2)$$

Where T_{aw} is the adiabatic wall temperature, T_c is the secondary air temperature, and T_∞ is the mainstream temperature. During the experiment, the temperature difference between adiabatic wall temperature and wall temperature $(T_{aw} - T_w)$ was maintained about 22K. In reality it is difficult to achieve a sufficiently adiabatic wall condition in this test plate, some correction must be made on the result of Eqn. (2). Follow the method used in Mick and Mayle [5], Eqn. (2) can be modified as;

$$\eta = \frac{T_{aw} - T_m}{T_c - T_m} = \frac{T_{ms} - T_\infty - \Delta T}{T_c - T_m} + \frac{q_{rad} + q_{cond}}{h(T_c - T_m)} \qquad (3)$$

Where T_{ms} is the measured surface temperature by infrared thermal camera, ΔT is the surface temperature correction, h is the heat transfer coefficient influenced by the injected secondary air, q_{rad} and q_{cond} are the radiation and conduction heat flux from the surface respectively. Value for ΔT is depend on the temperature difference between front and backside of the test plate $(T_c - T_w)$. In this study, base on the finding by Mick and Mayle [5], it is assumed that the value of ΔT is about 5% of $(T_c - T_w)$. For simplicity, we also assume that q_{rad} and q_{cond} cancel each other.

Results & Discussion

Figure 3 shows the laterally averaged effectiveness along the spanwise while Figure 4 show the centre line effectivess along the spanwise. From the figures, *M*=1.5 has the highest effectivess, followed by *M*=1.0 while *M*=2.0 has the lowest effectiveness. These show that *M*=1.5 is the optimum blowing ratio for this configuration of film holes.

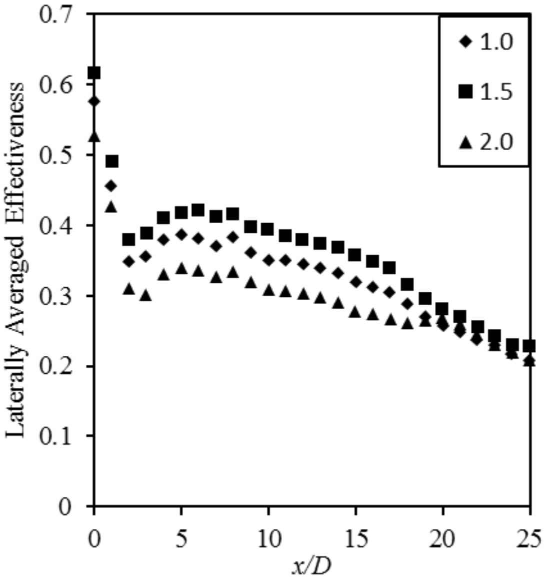

Fig. 3 Laterally Averaged Effectiveness

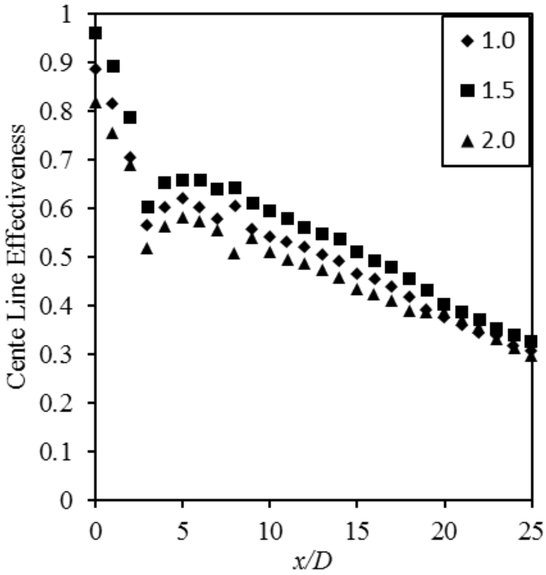

Fig. 4 Centre Line Effectiveness

In the current study, the most important objective is to improve the film cooling effectiveness of shallow angled holes with sister holes proposed by Ely et al. [4]. In order to find improvement of the result, this study proposed a 20° shallow angle to replace the 35° shallow angle proposed by Ely et al [4]. Figure 5 and Figure 6 show a significant improvement for both laterally averaged effectiveness and centre line effectiveness for every blowing ratio. With a smaller shallow angle, the lifting effect of secondary flow is reduced.

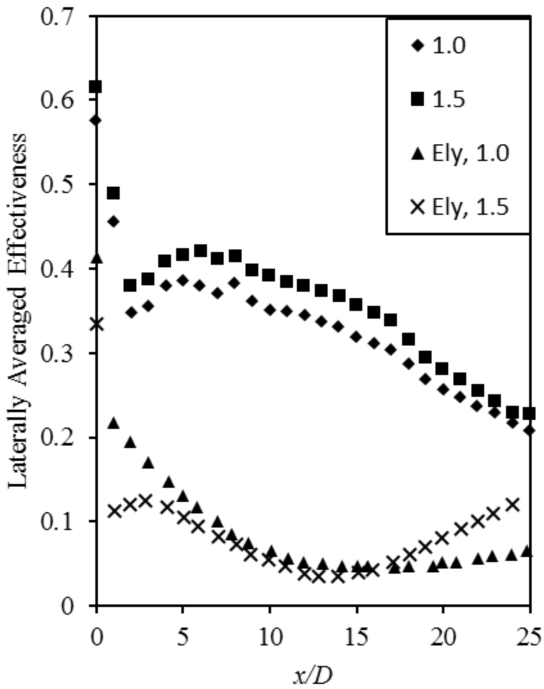

Fig. 5 Comparison of Laterally Averaged Effectiveness

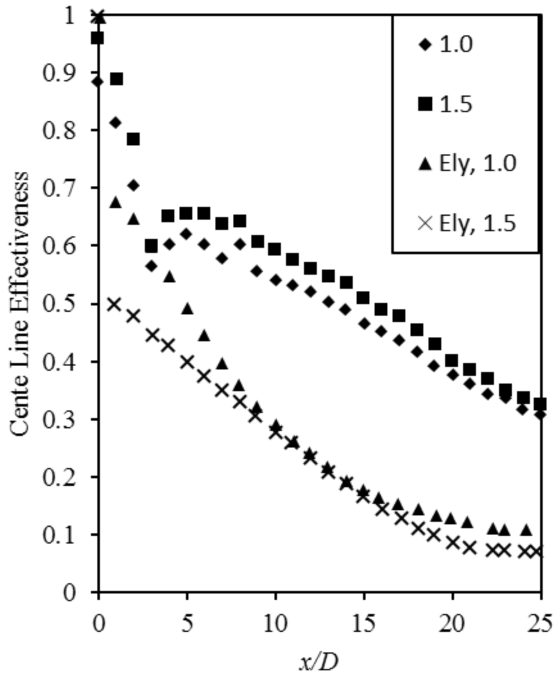

Fig. 6 Comparison of Centre Line Effectiveness

There are few factors which have possibly caused error in the study. First of all, the specification of the Venturi meter is not provided. To overcome this problem, the Venturi meter is calibrated by using a Pitot tube. Furthermore, the reading on the Infrared Camera is not exactly the same with the reading from thermocouple. Therefore, the calibration work has been done before taking thermal images.

Conclusion

The result showed a significant improvement compared to the previous study due to the use of smaller shallow angle, which is 20°. It is better than a shallow angle of 35° along the stream wise distance. The optimum blowing ratio is 1.5 for this study. A smaller shallow angle means a smaller injection angle which helps to reduce the jet lifting effect of secondary air flow. The sister holes from upstream help to push the secondary air flow from primary hole onto the wall which increases the film cooling effectiveness.

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