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

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Abstract. In order to increase the thermal efficiency of a gas turbine, the operating temperature has to be increased. This increment may cause the material of the blade to melt. Film cooling is a good option to solve this problem. Various studies has been done on film cooling include the shallow hole and sister holes. The present study focused on an experimental of film cooling effectiveness on shallow hole of 20° with upstream sister holes with 3 blowing ratios which are 1.0, 15 and 2.0. 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 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 study is carried out by using experimental method. Figure 1 shows the schematic diagram of the experimental setup. The apparatus used are open loop low speed wind tunnel for mainstream air supply, Wind Power Air Blower for secondary flow air supply, air heater to heat up air from secondary flow, Fluke 922 is used with Pitot Tube and also Venturi Meter for flow metering, thermocouple, and thermometer and infrared camera are used for temperature measurement. A test rig is fabricated for the test section.
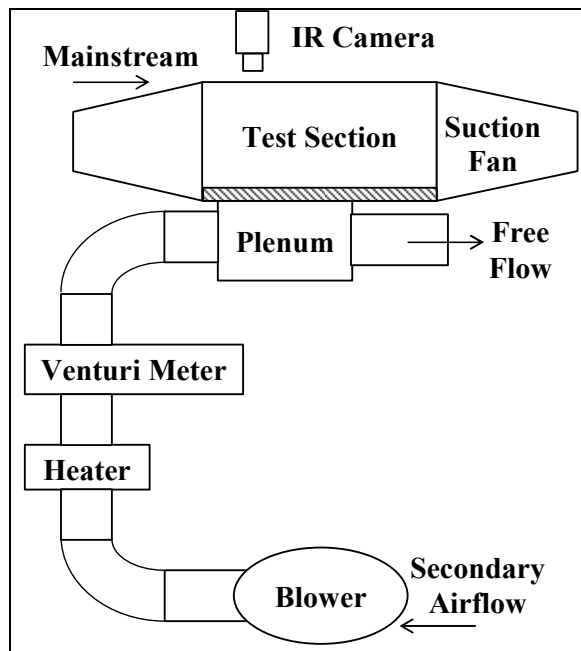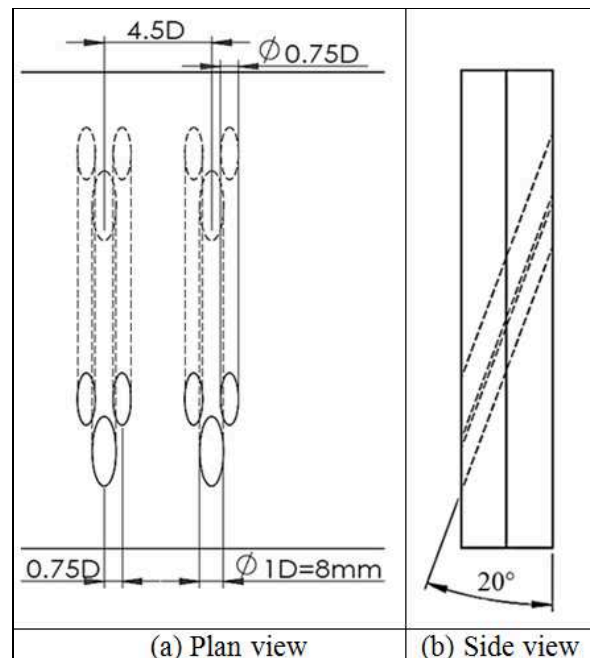

Fig. 1 Sketch of Experimental Setup

Fig. 2 Geometry of Shallow Hole with Upstream Sister Holes

Film Hole Geometry. The film hole geometry chosen is an array of film holes of 20° shallow angle with upstream sister holes. The diameter of the main hole, D is 8mm. Two sister holes with each 0.75D is placed. They are placed 0.75D upstream (*x/D*) and also lateral (*z/D*) to the main holes. The array consists of 5 sets of sister holes with a pitch of 4.5D. The data is collected from all 5 sets of holes and is compared with Ely et al. [4]. The drawing of the film hole is shown in Figure 2.

Data Analysis. Equation 1 is used to determine the blowing ratio.

$$M = \frac{\rho_s V_s}{\rho_m V_m} \tag{1}$$

where *M* is blowing ratio, ρ_s is density of secondary air, V_s is velocity of secondary air, ρ_m is density of mainstream air and V_m is velocity of mainstream air.

Equation 2 is used to determine the film cooling effectiveness.

$$\eta = \frac{T_w - T_m}{T_s - T_m}$$ (2)

where η is film cooling effectiveness, T_w is wall temperature, T_m is mainstream temperature, T_s is secondary flow temperature.

Results & Discussion

The experimental conditions have been planned before the experiment is carried out. However, the actual conditions have deviated a little from the planned conditions. The planned and actual experimental conditions are shown in Table 1.

Table 1 Experimental Conditions

Planned	T_m(°C)	30	30	30
	T_s(°C)	50	50	50
	M	1.0	1.5	2.0
Actual	T_m(°C)	29	29	29.5
	T_s(°C)	50.5	49	49.4
	M	1.025	1.499	1.948

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.
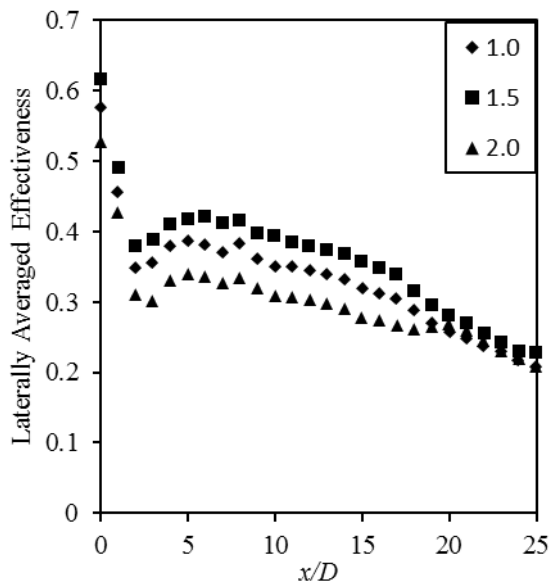

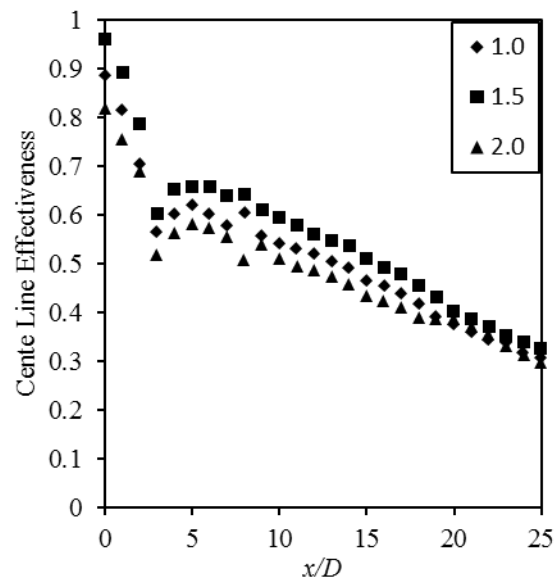Fig. 3 Laterally Averaged Effectiveness

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.
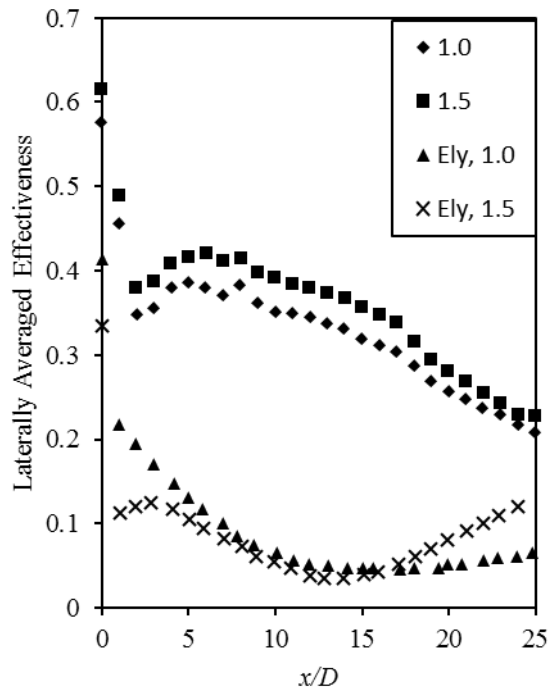
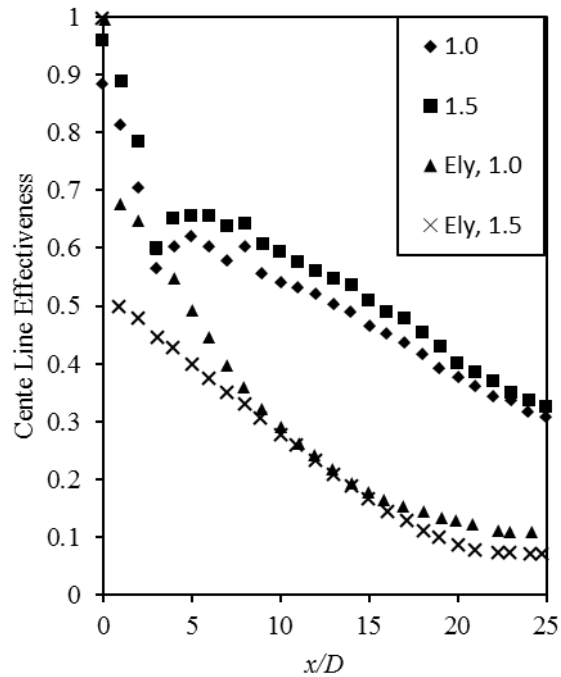Fig. 5 Comparison of Laterally Averaged Effectiveness

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.

References

[1] Han, J., Dutta, S., & Ekkad, S. (2013). Gas turbine heat transfer and cooling technology. 2nd Edition. Boca Raton: CRC Press, 2012

[2] Goldstein, R. J. (1971). Film cooling. Advances in heat transfer, 7(1), 321-379.

[3] Abdullah, K., Funazaki, K., Onodera, H., & Ideta, T. (2012). Experimental investigations on aero-thermal interaction of film cooling airs ejected from multiple holes: shallow hole angle. In Proceeding of ASME Turbo Expo.

[4] Ely, M. J., & Jubran, B. A. (2012). Film cooling from short holes with sister hole influence. In Proceeding of ASME Turbo Expo.

[5] Cengel, Y. A., & Boles, M. A.. Thermodynamics: an engineering approach. Volume 5. New York: McGraw-Hill. 2011

[6] Dhungel, A. (2007). Film cooling from a row of holes supplemented with anti vortex holes. Louisiana State University and Agricultural and Mechanical College: Master's Thesis.

[7] Ely, M. J., & Jubran, B. A. (2009). A numerical study on active film cooling flow control through the use of sister holes. Louisiana State University and Agricultural and Mechanical College: Master's Thesis.

[8] Funazaki, K. I., Kawabata, H., Takahashi, D., & Okita, Y. (2012). Experimental and numerical studies on leading edge film cooling performance: effects of hole exit shape and freestream turbulence. In Proceeding of ASME Turbo Expo.

[9] Huang, S., & Liu, Y. (2012). High rotation number effect on heat transfer in a leading edge cooling channel with three channel orientation. In Proceeding of ASME Turbo Expo.

[10] Kröss, B., & Pfitzner, M. (2012). Numerical and experimental investigation on the film cooling effectiveness and temperature fields behind a novel trench configuration at high blowing ratio. In Proceeding of ASME Turbo Expo.

[11] Liu, C. L., Zhu, H. R., Zhang, Z. W., & Xu, D. C. (2012). Experimental investigation on the leading edge film cooling of cylindrical and laid-back holes with different hole pitches. International Journal of Heat and Mass Transfer.

[12] Liu, K. C. (2009). Blowing ratio effects on film cooling effectiveness. Texas A&M University: Master's thesis.

[13] Sakai, E., Takahashi, T., & Agata, Y. (2012). Experimental study on effects of internal ribs and rear bumps on film cooling effectiveness. In Proceeding of ASME Turbo Expo.

[14] Saravanamuttoo, H. I. H., Rogers, G. F. C., Cohen, C., & Straznicky, P. V. (2009). Gas turbine theory. 6th ed. Edinburgh Gate: Pearson Education Ltd.

[15] Walsh, P. P., & Fletcher, P. (2004). Gas turbine performance. 2nd ed. Fairfield: Blackwell Science and ASME.