Computational Study of Pressure Side Film Cooling—Effect of Density Ratio with Combination of Holes

D. Radheesh, P. Ssheshan, N. Gnanasekaran and R.K. Panda

Abstract Film cooling is a proven cooling technique for gas turbine blades. The temperature distribution and flow phenomena vary with the suction and pressure sides. A computational investigation is carried out to understand the film cooling effectiveness and flow phenomenon on pressure side of a gas turbine aerofoil. A specific turbine blade profile is considered with combination of cylindrical and shaped holes in staggered fashion, oriented at different angles. Computations are carried out using the k-ϵ Realizable model available in the commercial code FLUENT 6.3. Meshing of the present model is done by using GAMBIT. The parameter variation considered for the present study is the blowing ratio (0.5–1.25) with an interval of 0.25 and three different density ratios (DR) 1.25, 1.5 and 2. The film cooling performance is discussed with effectiveness distribution on the interface wall. It is inferred that the film cooling performance enhances with increasing density ratio values. Also the optimum value of blowing ratio lies close to 0.75 for higher density ratio values of 2.

Keywords Film cooling · Combination of holes · Blowing ratio · Density ratio

D. Radheesh (✉)
Mechanical Engineering, SSN College of Engineering, Chennai, India
e-mail: radheeshd@gmail.com

P. Ssheshan
Mechanical Engineering, Easwari Engineering College, Chennai, India
e-mail: ssheshan.pugal@gmail.com

N. Gnanasekaran
Department of Mechanical Engineering, NIT Surathkal, Mangalore, India
e-mail: ngs.iitm@gmail.com

R.K. Panda (✉)
Smartgrid, Powergrid Corporation, Gurgaon, Haryana, India
e-mail: rajeshpanda@powergrid.in

A.K. Saha et al. (eds.), *Fluid Mechanics and Fluid Power – Contemporary Research*, Lecture Notes in Mechanical Engineering,
DOI 10.1007/978-81-322-2743-4_77

1 Introduction

The essence of Heat transfer is inevitable in today's Gas Turbine engines, due to the challenges of high inlet temperatures in order to provide betterment in its performance. Film cooling serves as an enticing research area among the external cooling methods, due to its intensified protection of the blade surface as well as convenience in its manufacturing process. Many researchers have assessed this technique to be an indispensable consideration for heat transfer studies. The interaction of the mainstream and coolant fluids makes the flow phenomena more complex especially in three dimensional modeling. The evolution of highly sophisticated computational facilities has zeroed down these complexities by providing efficient math models to solve in a most precise manner with less computational effort.

Goldstein et al. [1] concluded that the film cooling performance can be enhanced by using shaped channels. Walters and Leylek [2] provided a detailed analysis of streamwise injection with cylindrical holes using vorticity based approach. They concluded that the film-cooling performance was strongly affected by the secondary flow structure and by regulating the strength of the counter rotating secondary flow, the film cooling performance could be enhanced significantly. McGovern and Leylek [3] provided a detailed analysis of film cooling with compound angle injection for cylindrical holes using novel vorticity and momentum based approach. Their studies concluded that the distribution of effectiveness and heat transfer coefficient is highly influenced by the vortex structure arising due to the jet-in-crossflow in the interaction site. Jung and Lee [4] investigated the influence of inclination angle of film cooling holes and velocity ratio on temperature distributions and film cooling effectiveness. They observed that as the inclination angle increases there was an increased mixing between the free stream and injectant resulting in a decrease in maximum temperature of the injectant. They also observed that film cooling effectiveness increased with an increase in orientation angle. Azzi et al. [5] developed a mathematical model for film cooling predictions of simple and compound angle injections. They used three dimensional finite volume and multiblock technique for developing the numerical model and compared it with experimental results. They concluded that compound angle injection provided better film cooling protection than a simple angle injection for the same blowing ratio. Nasir et al. [6] have performed experiments to study the influence of compound angle injection on heat transfer coefficients and film cooling effectiveness. They concluded that compound angle injection greatly improves the film effectiveness but also causes higher heat transfer coefficients. Lin et al. [7] performed experiments to estimate the film cooling effectiveness of three inclined multi-hole configurations. They concluded that the blowing ratio has a smaller effect on cooling effectiveness for streamwise injection. Miao and Wu [8] used a computational approach to study the influence of blowing ratio and hole geometry on film cooling effectiveness and distribution of flow field by considering a flat plate with two rows of injection holes with staggered-hole arrangement. It was found that for laterally diffused, simple angle (LDSA) holes the counter rotating vortex pairs were nearly absent. Further, LDSA provided better film cooling effectiveness and gives a better lateral coverage of the coolant on the surface of the plate. Baheri et al. [9] provided a comparative numerical analysis on film cooling from a row of simple and compound-angle holes injected at 35° on a flat plate with different film cooling configurations. It was found that by providing trenched holes, counter rotating vortex pair at the exit of the jet had reduced and the cooling air spreading in streamwise direction had improved. Grizzle [10] studied the influence of density in film cooling on a flat plate with simple and compound angle holes and his results showed higher effectiveness at increased density rations. Gao et al. [11] analyzed the film cooling effectiveness of a HP turbine blade on sides. It was observed that the film cooling performance on the suction side was better than the pressure side. Also, it was seen that on both the sides, compound angle shaped holes provided higher effectiveness than axial shaped holes.

This paper focuses on studying the film cooling effectiveness on the pressure side with combination of cylindrical and shaped holes of different hole geometrical configurations using adiabatic method. It is evident that the performance of shaped holes is better than that of the cylindrical holes from the literature. Therefore, a combination of these holes is used to retain and integrate the advantages of the individual characteristics and provide an improved film cooling performance.

2 Mathematical Modelling

2.1 Geometric Modelling

The Geometric Modelling began with creating a wireframe model of a gas turbine airfoil using GAMBIT with proper co-ordinates, which is close to NACA 65 series. The lateral span is fixed to 40 mm. The modelled blade profile is shown in the Fig. 1. Six rows of shaped and cylindrical holes are made in the proper locations of the turbine vane to provide proper cooling performance. The first two rows being shaped holes oriented at 15° upstream and 30° downstream to enhance the cooling

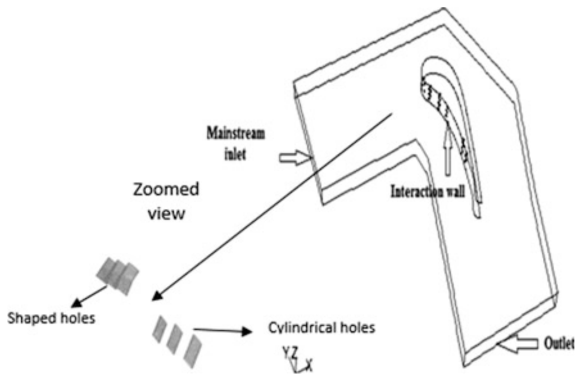


Fig. 1 Schematic of the geometry and boundary conditions

in the leading edge part. The third and fourth being cylindrical arranged in a staggered manner oriented at 45° to the mainstream jet and the last two rows are the combination of cylindrical and shaped holes also arranged in a staggered fashion. This staggered arrangement provides better coolant jet distribution along the blade pressure surface (PS). The coolant inlet diameter (D_c) is kept as 0.005 m while the corresponding mainstream inlet diameter is kept as 0.068 m.

2.2 Grid Generation and Independence Study

GAMBIT, a finite volume automatic grid generating tool was used for generating the mesh. The background grid consisted of three volumes viz. the inlet, interaction and outlet domains. A relatively coarse mesh was given to the inlet and outlet domains, since no flow interaction takes place. A finer grid is generated in the interaction domain in order to capture the complex flow interactions. Grid independence study was performed for three background grids consisting of approximately 690000, 1400000 and 1800000 cells, out of which the final grid size of 1400000 cells was chosen for carrying out the numerical simulation. The generated grid is shown in the Fig. 2 whereas the Grid independence plot is shown in Fig. 4.

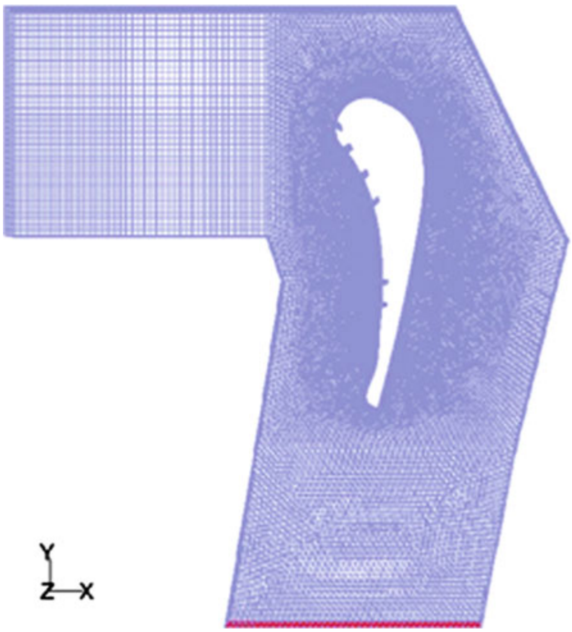


Fig. 2 Mesh used for present study

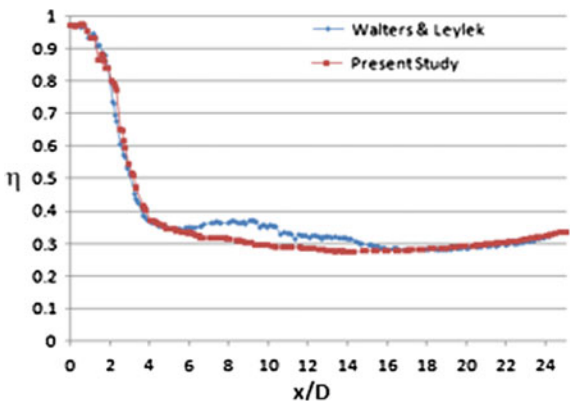
2.3 Boundary Conditions and Solving Methodology

The interface region of the mainstream and coolant stream is named as the interaction wall and the necessary inlet and outlet conditions are given to the corresponding boundaries where the remaining are kept as wall. The generated mesh was imported to FLUENT 6.3 to solve the governing equations viz. continuity, momentum, energy. k-ε Realizable turbulence model with standard wall treatment was adopted for this solution. All the above equations are upwinded in the second order scheme. Three different density ratios (DR) of 1.25, 1.5 and 2.0 were investigated for evaluating its performance with a constant mainstream temperature (T_m) of 673 K and the corresponding coolant temperatures (T_c) are 538, 449 and 337 K. The blowing ratios (M) of 0.5, 0.75, 1, and 1.25 were examined to compare the maximum attainable cooling effectiveness for a constant mainstream velocity (U_m) of 30 m/s.

2.4 Numerical Validation

The present model is validated with the Computational works of Walters and Leylek [2]. The streamwise averaged effectiveness is compared for the cylindrical hole performance from its trailing edge and the plots in Fig. 3 shows that the present work agrees well with Walters & Leylek model with a minimum error (Fig. 4).

Fig. 3 Plots of numerical validation



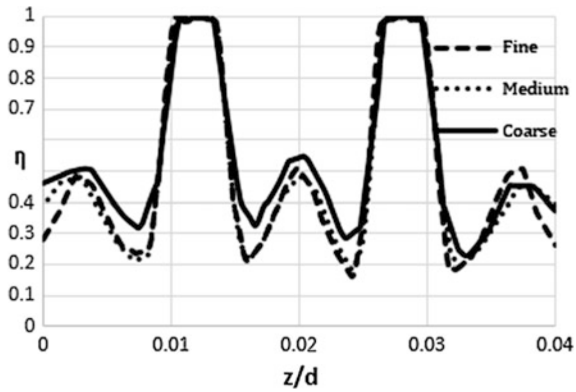


Fig. 4 Plots of Grid Independence study

3 Results and Discussions

3.1 Temperature Variation

To discuss the variation of temperature for three different DR cases 1.25, 1.5 and 2, a plane that cuts cylindrical and shaped hole is made and the contours are shown in the respective Figs. 5, 6 and 7. At higher blowing ratio (M) values, jet lift off takes place for cylindrical holes whereas the jet from the shaped hole remains attached to the blade surface thus providing a protective lower temperature distribution along the trailing edge. Also, with increasing DR values the cooling performance increases as it is evident from the temperature contours for DR = 1.5 and 2. This is due to the effective coolant distribution. Hot spots are formed in the leading edge

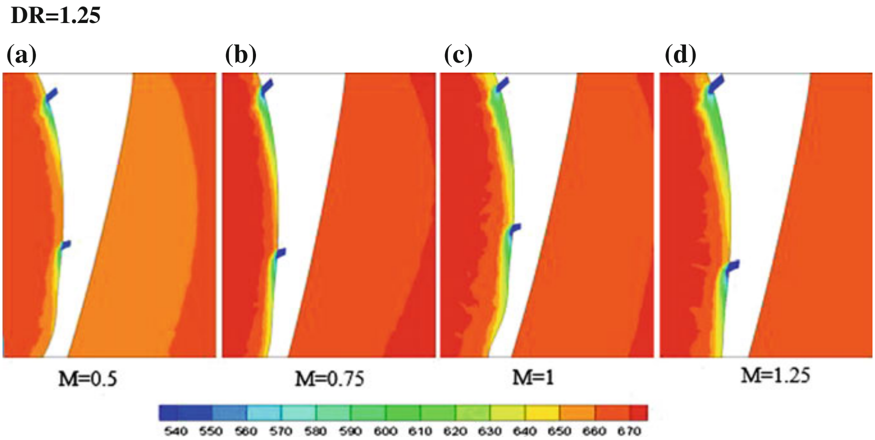


Fig. 5 Contours of Temperature variation for DR = 1.25

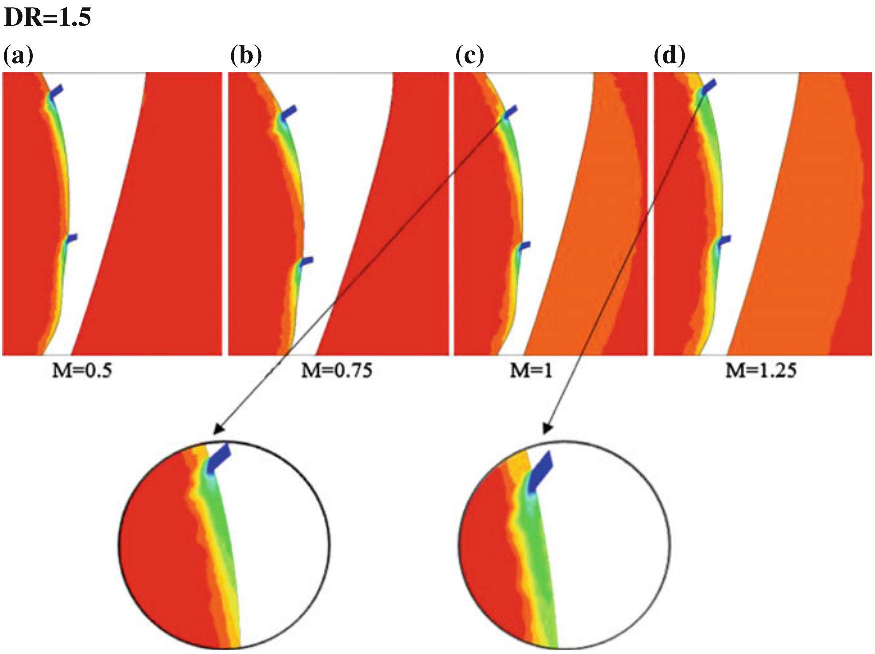


Fig. 6 Contours of Temperature variation for DR = 1.5

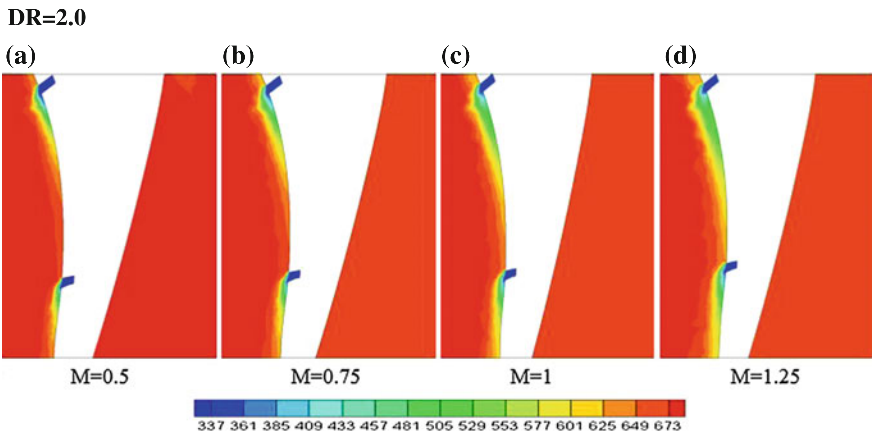


Fig. 7 Contours of Temperature for DR = 2.0

upstream region due to the action of jet-in-crossflow between the hot mainstream and the coolant. These hot spots are formed due to the direct exposure of the blade surface to the hot mainstream (Fig. 8).

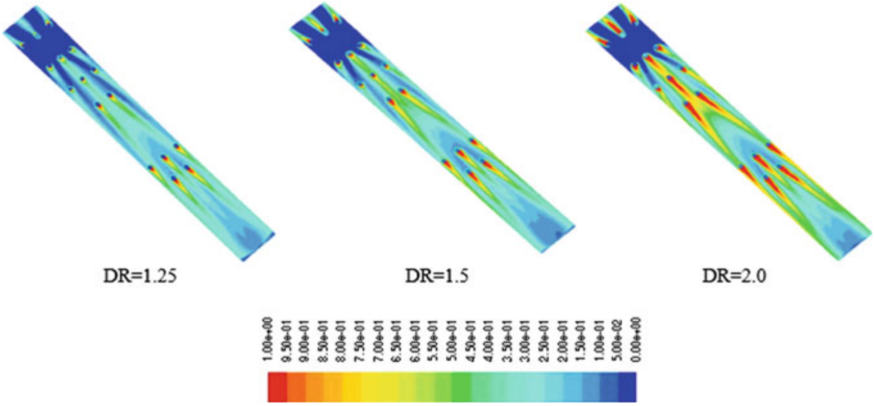


Fig. 8 Contours of Effectiveness for M = 1 for different DR values

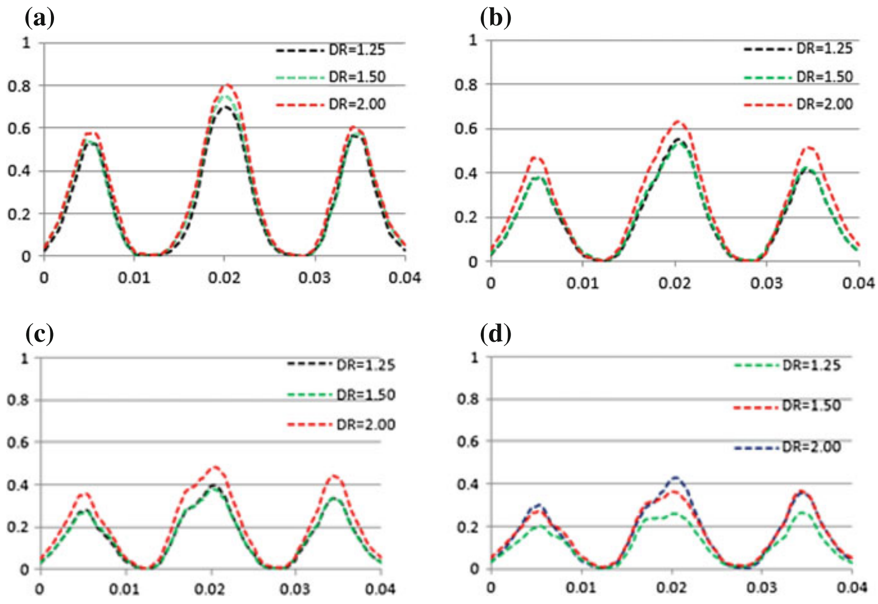


Fig. 9 Plots of Spanwise effectiveness near LE region. **a** M = 0.5, **b** M = 0.75, **c** M = 1, **d** M = 1.25

3.2 Effectiveness Distribution

The film cooling effectiveness is discussed with the effectiveness contours followed by the comparison of span-wise averaged effectiveness plots at two locations viz., the leading edge (LE) and trailing edge (TE) zones for DR values of 1.25, 1.5 and 2 presented in the Fig. 9. For all the cases the latter has higher effectiveness values compared to the former. This arises due to the formation of hot spots in the leading edge region. These hot spots are formed due to the jet lift-off action at higher M values that leads to the movement of CRVP from the blade wall. These CRVP arises due to the interaction of jet-in crossflow thus making the blade surface to get directly exposed to the hot mainstream. At higher density ratio (DR) values of 2, the film cooling effectiveness is increased for all the blowing ratio values. This is due to the increase in the lateral spreading of the cooling at higher DR values. The plots of span-wise averaged effectiveness for leading and trailing edge regions are shown below in the corresponding Figs. 9 and 10.

From the Fig. 9, it can be observed that the span-wise effectiveness is higher at lower M values and decreases with increasing M values with respect to the leading edge region. In contradiction to that there is an increase in the corresponding value near the trailing edge region with the increasing M values. The highest effectiveness for leading edge occurs at lower M values but in the trailing edge region the results

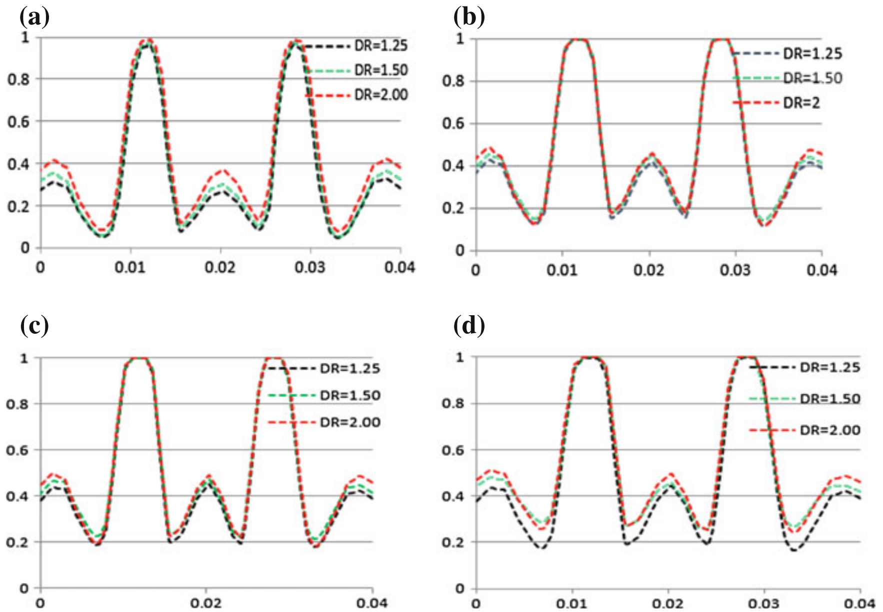


Fig. 10 Plots of Spanwise effectiveness near TE region. **a** M = 0.5, **b** M = 0.75, **c** M = 1, **d** M = 1.25

are just the reverse. The effectiveness distribution is maximum at DR = 2 for all the blowing ratios. Therefore for DR = 2, the optimum effectiveness value lies at M values close to 0.75 for this combination of holes configuration.

4 Conclusions

Computational investigations are carried out on a pressure side of a gas turbine airfoil with combination of shaped and cylindrical hole with different orientations to study the film cooling performance. The film cooling performance is discussed with the temperature variation followed by the effectiveness distribution and the following results are observed.

(i) There is relatively lower temperature distribution along the trailing edge region and hot spots are formed near the leading edge upstream region. This is because, the shaped holes have comparatively reduced jet lift-off action thus getting attached to the blade wall.
(ii) The span-wise averaged effectiveness of LE region is higher at low M values but decreases with increasing M values and vice versa for TE region. Overall the maximum effectiveness for all blowing ratios occurs at DR = 2.

An optimum value of blowing ratio (M) value of 0.75 can be maintained for DR = 2 for the entire blade cooling performance along the pressure side.

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