An investigation on film cooling with a coalition of forward and backward injection

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Abstract. Full coverage film cooling, also known as effusion cooling, is used to protect combustor liner from high temperature gases in the gas turbine. Numerical analyses are carried out to investigate and compare cooling performance of two arrangements, namely mix and opposite injections composed of forward as well as backward injection holes. Mix injection arrangement consists of rows of cooling holes injecting in alternate backward and forward directions, while in opposite injection configuration holes inject just in the opposite directions. Computational study is carried out at various velocity ratios ($VR$) from 0.5 to 5.0. Forward and backward injecting cooling holes, in both the configurations, are inclined at $30^\circ$ with respect to mainstream. Adiabatic film cooling effectiveness is estimated along stream wise as well as lateral directions. Except front few rows of cooling passages (holes), configuration with opposite injection shows superior cooling than mix injection at high velocity ratios. Developed effusion or diffusion film layer is seen for both mix and opposite injection configurations, at high velocity ratios, but it occurs bit early for opposite injection. In opposite injection, fluctuations in cooling effectiveness along stream wise direction are higher as compared to mix injection at all velocity ratios.

Keywords: film cooling; effectiveness; mix injection, coalition

1. Introduction

In order to meet increasing power requirements, latest cooling techniques have allowed turbine designers to increase the turbine inlet temperature to the levels of $1700^\circ$C which are robust and strong and beyond the metallurgical restriction of hot turbine components. The turbine designers are always concerned with effective use of the cooling air [1]. Film cooling has set of holes placed at liner surface through which cool air, extracted from compressor, is ejected to create a protective barrier between the hot main flow and liner surface. Film cooling is mainly affected by geometry, inclination, size, shape, orientation, and arrangement of holes as well as surface roughness and various other aero-thermal conditions [2-4]. Generally cylindrical or shaped holes are being used in film cooling. For forward injection, film cooling performance of cylindrical holes is limited due to the formation of kidney vortex and jet penetration at high velocity ratios which is not prominent in case of shaped holes due to diffusion.
phenomenon, at the exit of shaped holes. However, cylindrical holes are straightforward and easy to fabricate and hence these holes with different orientations have been researched and have shown better cooling characteristics than conventional forward injection [5].

Scritto et al. [6] have performed a lot of experiments on multi-holed film cooling. They have studied flow behaviour and characteristics of effusion film layer. Results of their experiments show strong and positive influence of momentum flux ratio on film cooling effectiveness. Yang et al. [7] studied effect of stream wise and lateral hole-to-hole spacing on cooling performance and development of effusion film layer at different velocity ratios. Reaz Hasan et al. [8] investigated performance of effusion cooling on a flat plate at various velocity ratios (0.25 to 1.5). Outcome of both the studies demonstrated better cooling at higher velocity ratios.

Orientation of cooling holes with respect to mainstream flow is one of the major influencing parameter that has drawn attention of various researchers in the past decade. Cylindrical holes with backward or reverse injection have shown remarkable improvement in cooling protection as compared to conventional downstream injection. Oguntade et al. [9] investigated both experimentally and numerically and concluded that the film cooling with backward injection gets improved. Chen et al. [10] found from their experiments that converse injection with cylindrical holes intensified cooling effectiveness but it was not true for reverse injection with shaped holes.

Andrews et al. [11] compared film cooling performance of forward and reverse injections. They concluded that backward injection demonstrated better cooling than forward injection at low blowing ratios, but the same was not true at high blowing ratios. Singh et al. [12] investigated film cooling experimentally as well as numerically on film cooling with forward and backward injections. They concluded that averaged cooling effectiveness with backward orientation of injection was higher than conventional downstream injection.

Numerical and experimental studies on film cooling, available in open literature, have generally been performed on adiabatic flat plates [13] to reduce complexity. Sehjn et al. [14] have conducted tests on film cooling with several rows of cylindrical holes with three different arrangements; forward injection, backward injection and mix injection. Inclination of holes was 35° for both forward and backward holes. They concluded that arrangements with mix injection holes resulted best cooling protection.

Although many studies have been carried out on effusion cooling with forward and backward injections, few literatures are available on film cooling combining both forward and reverse holes. In companion papers [15-16], full coverage cooling performance on an adiabatic plate was studied with the configuration having forward, backward, mix and opposite injection holes. It was concluded that the effectiveness of film cooling for mix and opposite configurations are much higher as compared to forward and backward injection configurations. In the present study, an attempt is made to bring out beneficial features of the two configurations by comparison, so that proper selection out of these two can be made for a typical application. The detailed configurations of opposite and mix injections can be found in companion papers [15-16].

2. Computational Methodology

2.1 Computational Model

In this article 3D Computational study is carried out for two cases; opposite injection and mix injection for the computational domain is shown in figure 1 (a-g). Schematic of flow is given in figure 1 (c). The two cases are studied at velocity ratios of $VR = 0.5, 1.0, 2.0$ and $5.0$. Air is used as a working fluid for both primary and secondary flows. Forward injection hole injects towards mainstream flow and backward injection hole inject opposite to mainstream as shown in figures 1(d) and (e). Opposite and mix injection configurations are shown in figures 1 (f) and (g). Injected cool air forms a protective layer between the hot main stream flow and surface to be cooled, thus reducing convective heat transfer to the surface. Both forward and backward injection holes are inclined at an angle of $30^\circ$. Cylindrical Diameter ($d$) of the cooling holes is 1.0 mm. Span wise and stream wise hole-spacing are same
(p/d=s/d=4.9) [6, 8] and distribution of cooling holes on adiabatic wall follows long diamond (LD) pattern [8]. The computational domain is kept 50d high [7]. Due to the periodic nature of boundary, width (z-direction) of the computational domain is taken as unit hole-to-hole pitch (p/d=4.9), as shown in figure 1 (b). Distribution of cooling holes on adiabatic plate is shown in figure 1 (d). For all the configurations, the centreline of first set (row) of cooling holes is at x=20d from the inlet and the last row of cooling holes is at x= -50d from the end of the computational domain. Cooling holes of 20 rows are involved in all the configurations.

Figure 1. (a) Computational domain in 3D; (b) Distribution of holes; (c) Schematic of flow; (d) Forward injection hole; (e) Backward injection hole; (f) Opposite injection configuration; (g) Mix injection configuration.

2.2 Governing Equations
ANSYS FLUENT solver is used to solve conservation equations of mass, momentum and energy and equation of state. These equations may be found in detail in Versteeg et al. [17]. A non-dimensional
parameter ‘adiabatic cooling effectiveness ($\eta_{ad}$)’ is used for defining the cooling performance which is given by the following equation:

$$\eta_{ad} = \frac{T_g - T_{aw}}{T_g - T_c}$$

(1)

where $T_g$ is main stream temperature, $T_{aw}$ is the temperature of wall if there is no conduction to and through the wall and $T_c$ is temperature of cool air.

2.3 Numerical computations

Generation of 3D grid for the simulation domain is performed in Gambit pre-processing software. To capture the flow physics in the boundary layer precisely, very fine grid is generated near the wall as well as at the exit area of coolant holes. Non-dimensional boundary layer thickness ($y^*$) values are controlled below 1.0 throughout the adiabatic wall. Realizable $k$-$\varepsilon$ turbulence model with enhanced wall treatment has been used in this study [18, 19]. Incompressible flow is used for both types of flow in the 3D computational domain because the value of Mach number nowhere exceeds 0.3.

The convergence criterion is set as follows:
(a) All residual values, except energy, are below $10^{-4}$ which should be less than $10^{-6}$.
(b) Mean surface temperature of wall does not differ for consecutive iterations.

2.4 Boundary conditions

Velocity ratio ($VR$), a dimensionless parameter, is defined as;

$$VR = \frac{V_c}{V_g}$$

(2)

where $V_c$ and $V_g$ are inlet velocities of coolant and main stream flows respectively. Velocity ratio represents strength in the coolant jet relative to the main stream flow. Mainstream and coolant inlets are defined as velocity inlets. Mainstream flow velocity is taken as, $V_g = 50$ m/s throughout this study whereas coolant velocity $V_c$ depends on velocity ratio. For the two configurations, inlet temperature of the mainstream flow ($T_g$) is taken as 350K while inlet temperature of coolant jet ($T_c$) is 300K. The wall of the adiabatic plate is modelled as 'adiabatic no-slip condition'. The two planes (top and transverse) are assigned 'symmetry' boundary condition.

2.5 Grid independence study and validation of numerical approach

The grid independence test is performed with forward injection cooling holes at $VR=0.5$. Nearly 1.6 million cells are involved in numerical computation. To validate the numerical approach, outcome of numerical investigation with forward injection configuration is compared with the experimentally available results of Scrittore et al. [6] at velocity ratio, $VR=3.2$. Details of grid independence study and validation of numerical approach can be found in companion papers [15, 16].

3. Results and Discussions

3.1 Laterally averaged cooling effectiveness

Figures 2 (a) and 2 (b) compares diffusion of laterally averaged cooling effectiveness of mix and opposite injection respectively with forward and reverse injections along stream wise direction at velocity ratio of 2.0 ($VR=2.0$). Both mix and opposite injection configurations show greater and over uniform cooling as compared to other (forward and backward) configurations. These results are obtained from companion papers of Mishra et al. [15-16] and shown here for better clarity.
Figure 2. Distribution of laterally averaged cooling effectiveness at velocity ratio (VR= 2.0) for (a) Forward, Reverse and Mix; (b) Forward, Reverse and Opposite.

Figure 3 shows comparison in distributions of laterally mean cooling effectiveness along the length of plate for mix and opposite injections, at various velocity ratios mainly from 0.5 to 5.0. In opposite injection, regions where two holes inject towards each other, show higher effectiveness values than mix injection in the same regions. However, the regions where two holes inject away from each other, in opposite injection, the effectiveness value are smaller than that with mix injection for the same regions.

Figure 3. Comparison of laterally mean cooling effectiveness for opposite and mix injection at velocity ratios of (a) 0.5; (b) 1.0; (c) 2.0; (d) 5.0.

Therefore, there is large fluctuation in averaged effectiveness values in opposite injection configuration. Figures 3 (a) represents effectiveness for opposite and mix injection at 0.5 velocity ratio.
(VR= 0.5). At this velocity ratio, the two arrangements exhibit similar performance except narrow upstream region of the perforation where mix injection configuration is better. A significant improvement in cooling protection with opposite injection atop mixed injection is noticed when velocity ratio is increased from VR=0.5 to 5.0, as shown in Figure 3. This improvement is even more at subsequent to perforated region. High velocity ratios, VR= 2.0 and 5.0 (both opposite and mix injections) show a sudden rise in film cooling effectiveness near front few rows of multi holed region, as shown in figures 3 (c) and 3 (d). However, the averaged film cooling effectiveness of opposite injection is higher than mix injection. But mix injection gives more uniform cooling. The fluctuation in cooling effectiveness is large at low velocity ratio for both mix and opposite injection holes but at high velocity ratios this fluctuation is less in mix injection. At velocity ratios, VR=0.50-1.0, momentum in secondary flow jet is low as compared to main stream flow and hence effusion film layer never attains developed stage and film cooling effectiveness gradually decreases in downstream direction beyond the perforated region. Whereas at high velocity ratios, VR=2.0 and 5.0, due to high momentum in secondary flow, the effusion layer reached developed phase at very early and continues still beyond perforated region. Mix and opposite injections have an advantage of continually increasing film cooling effectiveness till the progress of effusion layer from advanced stage.

3.2 Variation of temperature profile of wall

Figures 4 and 5 exhibit the temperature profiles of opposite and mix arrangements on the adiabatic wall at various velocity ratios (VR), 0.50 - 5.0. The adiabatic wall temperature is strongly influenced by spread of coolant jet in lateral direction.

In opposite injection, the lateral spread of coolant jet is large in the regions where two holes inject towards each other and oblique spread of coolant stream is low where the two holes inject away from each other. This difference of oblique spread of coolant is not present in mix injection configuration. Thermal potential core exists on the wall at very low velocity ratio, VR=0.5, it supports till last few rows of the multi holed region as shown in figure 4. The existence of this high thermal potential nucleus in the stream wise direction decreases with elevation in velocity ratio for both the arrangements.

In opposite injection, the regions where the two holes inject towards each other, due to oblique spread of the coolant layer, the coverage area of coolant across the holes increases and low space remains available for primary flow to infiltrate into this. Hence this region gives higher film cooling effectiveness. Whereas when the two holes inject away from each other the whole region across the holes is available for primary flow to enter into it, resulting in low cooling effectiveness in the region. For opposite
injection, transformation of film layer from advancing to developed phase takes place at 7th row for velocity ratio 5.0. Whereas it happens at 10th row for mix injection, as shown in figure 6.

![Figure 6. Distribution of film cooling effectiveness in lateral direction at VR = 2.0](image)

(a) Mix injection; (b) Opposite injection.

### 3.3 Lateral diffusion of film cooling effectiveness

Figure 6 shows lateral diffusion of cooling effectiveness mainly for mix and opposite injections at velocity ratio, VR=2.0. The cooling effectiveness values are calculated at the outlet of various rows namely 1, 5, 10, 15 and 20. The cooling effectiveness shows almost negligible deviation along lateral direction beyond Row 15, for both the configurations but its averaged value steadily increases towards Row 20 for mix injection as shown in figure 6 (a). However, lateral deviations in the cooling effectiveness are higher for mix injection arrangement at the front rows of multi-holed region. Opposite injection arrangement shows higher and constant film cooling effectiveness in downstream region. It shows its superiority over mix injection and existence of developed effusion film layer. Hence, it is evident from this study that at high velocity ratio, the laterally mean film cooling effectiveness values are higher and fluctuations in lateral distribution in cooling effectiveness is less in opposite injection.

### 4. Conclusion

Numerical study is performed to compare film cooling attainment of mix and opposite injection arrangements. Laterally or oblique averaged cooling effectiveness mainly depends on the lateral as well as stream wise spreading of the secondary flow jet. Moreover, lateral spreading is less at low velocity ratios as compared to that at high velocity ratios. The region in opposite injection, where the two holes inject towards each other, lateral spread increases while lateral spread decreases when two holes inject away from each other. This increase and decrease in lateral spread of coolant jet is main reason for the large fluctuations in averaged film cooling effectiveness in opposite injection which is not seen in mix injection. Opposite injection supports early development of effusion film layer as compared to mix injection. Opposite injection also gives better cooling coverage in lateral direction, at high velocity ratios. At high velocity ratio, mix injection gives less fluctuations in averaged cooling effectiveness in stream wise direction whereas, in lateral direction, fluctuations in cooling effectiveness is less for opposite injection. Moreover, higher cooling effectiveness values are evident with opposite injection at high velocity ratios. Form the fabrication point of view, opposite injection holes are difficult to manufacture and this difficulty may widen further with low thickness of combustor liner wall.
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