Conjugate heat transfer from a microchannel embedded impingement cum film cooled-flat plate

A K Jaiswal*, P S Mahapatra and B V S S Prasad

Department of Mechanical Engineering, IIT Madras, Tamil Nadu 600036, India
*Corresponding Author: me17d039@smail.iitm.ac.in

Abstract. A computation fluid dynamics analysis is presented to investigate the effect of placing a microchannel inside a flat plate. A microchannel embedded flat plate with 25° angled 175 film holes in staggered form is considered in the present work. A Conjugate heat transfer analysis is done to determine the efficiency of cooling. Simulations were carried out, and subsequently, a parametric study was conducted to observe the effect of variation of blowing ratios. The temperature distribution is observed to be more uniform due to the presence of the microchannel, resulting in a lesser thermal gradient in the solid plate. It is also noted that overall effectiveness increases with the blowing ratio. The maximum increase in overall effectiveness due to the microchannel is about 30% for the blowing ratio of unity.

1. Introduction
In the modern-day, high power with better efficiency is achieved by increasing the temperature of a turbine’s hot flue gas. These temperatures are generally in the order of melting point of the material of construction. So there is always a requirement for better cooling techniques for maintaining the temperature in the safe working limits. Over the past decades, many cooling methods have been developed, like convection cooling, film cooling, and impingement cooling [1-3].

Many literatures considering the flat plate as a solid wall of the blade are available. The effect of $L/D$ ratio, inclination angle, compound angle, blowing ratio, density ratio, and turbulence intensity has been presented in film cooling. For forecasting, the more reliable and accurate results of blade cooling researchers have focused on three-dimensional conjugate heat transfer analysis [4]. Film cooling is used to maintain a lower temperature of the outer blade wall, whereas impingement cooling works as localized internal cooling. So it is always better to use spent air after impingement for film cooling. The investigation done by Panda and Prasad [5], and Xie et al. [6] revealed that impingement cooling, coupled with flat plate film cooling, is an efficient technique for the turbine blade. Computational analysis done by Jaiswal et al. [7] revealed that the inclusion of microchannel inside film-cooled curved surface enhances the cooling efficiency. Much work has been done to observe the microchannel’s cooling effect in a solid plate [8]. However, the inclusion of a microchannel in a film-cooled plate is sparse. The present work’s motivation stems from investigating the influence of placing a microchannel in the solid wall of a film-cooled flat plate.

2. Methodology
A numerical model used in the present investigation is shown in figure 1. Uniform mass flow rate ($\dot{m}_{coolant} = 0.007 \, \text{kg/s}$) and temperature ($T_{coolant} = 303 \, \text{K}$) are used for coolant inlet. Similarly, a uniform temperature ($T_{mainstream} = 318 \, \text{K}$) and velocity are specified at the mainstream flow inlet. For reducing the computational cost and size symmetry was implemented (see figure 1). For different
The Reynolds number for mainstream was varied from 83328 to 250764 for achieving different blowing ratios while Reynolds number is kept constant at 1078 for the impingement hole inlet.

The finite volume-based commercial software Fluent 18.2 was used for the present numerical work. The mass, momentum and energy conservation equations are solved along with the turbulence model equations. The steady-state solver with a two-equation SST k-w turbulence model was adopted for calculating the turbulence quantities [6, 9]. No-slip boundary condition for all solid-fluid interfaces and coupled boundary condition \((T_{\text{fluid}} = T_{\text{solid}} \text{ and } k_{\text{fluid}} \frac{\partial T_{\text{fluid}}}{\partial x} = k_{\text{solid}} \frac{\partial T_{\text{solid}}}{\partial x})\) for all solid to solid and solid to fluid interfaces were implemented. The pressure-based solver with SIMPLE pressure-velocity coupling and second-order upwind was used as a discretization scheme for all parameters. For monitoring the convergence, the difference of area-weighted average temperature of interaction surface and mainstream was used. The solution is considered to be converged when there is no significant change (less than 0.1%) for 1000 consecutive iterations. The residual criteria were set \(10^{-8}\) for energy and \(10^{-6}\) for continuity, momentum, and turbulence quantities.

A different grid size of 3.1, 4.2 and 5.6 million was used to analyse the grid sensitivity test. For this, overall effectiveness was considered and no significant changes (less than 0.1%) were found for 4.2 and 5.6 million mesh sizes. So the grid size of 4.2 million was used for further investigation.

2.1. Computational model

In the present computational analysis, a flat plate of 99\(d\) \(\times\) 75\(d\) with 175 film holes of diameter \(d = 5\) mm is used, which are making inclination angle \(\alpha = 25^0\) with the interaction surface (see figure 1a). The arrangement of film holes is in a staggered way with an axial pitch of 6.96\(d\) and a transverse pitch of 4.94\(d\). Studies on figure 1a are considered as the base (first) case.

For investigating the effect of the microchannel, a rectangular channel \((93d \times 69d)\) of constant height 2 mm was created inside the solid plate (see figure 1b). For this second case where the microchannel is embedded in a solid wall, 175 impingement holes of diameter 5.25 mm were drilled on the bottom side of the plate (see figure 1c).

**Figure 1.** Schematic diagram of flow domain with (a) film cooled plate, (b) microchannel embedded film cooled plate and (c) arrangements of impingement holes and film holes and comparison of numerical data with experimental data of Kohli & Bogard [10] and computational data of Na and Shih [11] (d) laterally averaged adiabatic effectiveness \(\eta\), (e) centerline adiabatic effectiveness \(\tilde{\eta}\).
2.2. Validation
The computational model has been validated by comparing with the adiabatic effectiveness values for blowing ratio $M = 0.5$ published by Kohli and Bogard [10] and Na and Shih [11]. For this, a test plate with $35^0$ angled film holes ($L/D = 2.8$) and other parameters was separatedly considered according to Na and Shih [11]. It can be observed from figures 1d and 1e that the present computational results are in good agreement with computational results published by Na and Shih [11]. Both computational works reveal that numerical results are over predicting the centerline adiabatic effectiveness $\eta = (T_{\text{mainstream}} - T_{\text{adiabatic wall}}) / (T_{\text{mainstream}} - T_{\text{coolant out}})$ and under-predicting the laterally averaged effectiveness of the experimental results of Kohli and Bogard [10]. In comparison with the experimental observation, the numerical predictions show a larger region of longitudinal spreading and a smaller region of lateral spreading of coolant on the interaction surface.

3. Results and Discussions
In figure 2a, the distribution of centreline overall effectiveness $\Phi = (T_{\text{mainstream}} - T_{\text{wall}}) / (T_{\text{mainstream}} - T_{\text{coolant}})$ for different blowing ratios have been presented. It can be noted that upstream of the 2nd row of film holes’ effectiveness increases with blowing ratio and decreases in between the 2nd and 4th row of film holes. The tendency is reversed again in the downstream direction of the 4th row. In the case of microchannel-based impingement, cum film cooling (IFMC) effectiveness is higher than only film cooling (FC) case for all blowing ratios. This is due to increased convection heat transfer in the microchannel. Higher fluid temperature can also be seen at the film holes outlet in the IFMC case.

The stream traces distribution with temperature profile on a y-z plane passing through the line CD ($x/d = 27$) is shown in figure 2b. It is observed from the figure that coolant forms counter-rotating vortex pair (CRPV) after coming out from film holes. The size of CRPV is increasing with the blowing ratio leading to a reduction in effectiveness at $x/d = 27$.

![Figure 2](image_url)

**Figure 2.** Distribution of (a) laterally averaged overall effectiveness $\Phi$ for a film cooled plate and microchannel embedded film cooled plate for different blowing ratios, and (b) stream traces with temperature contour on a y-z plane passing through line CD for different blowing ratio.

In figures 3a and 3b distribution of stream traces with temperature is shown on the symmetry plane. It can be seen that lower uniform material temperature is maintained in the solid wall due to enhanced convection cooling. Jetting effects can also be seen in the film holes, which causes a lower momentum zone near the downstream wall and a higher momentum zone near the upstream wall. The distribution of stream traces on a mid-plane is shown in figure 3c. It can be seen that after impingement, wall jets are formed, and before entering into film holes, wall jets interact with neighbour jets.
The area-weighted averaged overall effectiveness ($\Phi_{avg}$) values on the interaction surface are presented in table 1 for the different blowing ratios to describe a comprehensive evaluation. A maximum increment of 29.91% was observed for blowing ratio $M = 1$.

![Temperature Contour](image)

**Figure 3.** Distribution of stream traces superimposed with temperature contour on symmetry plane (a) filmed cooled plate, (b) microchannel embedded film cooled plate, and (c) stream traces on a mid-plane at the height of 6 mm from the bottom of the plate.

**Table 1.** Area weighted averaged overall effectiveness ($\Phi_{avg}$) on interaction surface.

| Blowing ratio | FC  | IFMC  |
|---------------|-----|-------|
| $M = 0.5$     | 0.43| 0.55  |
| $M = 1.0$     | 0.45| 0.58  |
| $M = 1.5$     | 0.48| 0.60  |

4. Conclusions
A conjugate heat transfer analysis has been performed to study the effect of microchannel-based combined impingement cum film cooling of a flat plate. It is found that the effectiveness increases by a maximum of 30% for microchannel embedded film cooled flat plate. Besides, a lower uniform surface temperature distribution is obtained in microchannel-based cooling. This works provides that microchannel-based near-wall cooling will maintain the lower material temperature.

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