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Film Cooling Effectiveness Using Cylindrical and Compound Cooling Holes at the End Wall of Combustor Simulator

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Abstract – *A numerical 3-D simulation has been performed to investigate fluid flow and heat transfer characteristics of a film cooling injected through cylindrical and compound angle oriented holes with alignment angle of 30 degree adjacent to the end wall surface for a Pratt and Whitney gas turbine engine by ANSYS FLUENT 14.0. The results indicate that employing compound angle cooling holes injection gives much better protection to the components rather that obtained when simple angle cooling holes were used.*

Keywords: Compound Hole, Cylindrical Hole, Gas Turbine, Film Cooling Effectiveness

1.0 INTRODUCTION

According to the literature pertaining this study, the first area of outlet that faces hot gases in the combustor is the end of wall surface therefore, cooling of this area is very important in order to protect the critical components of both downstream and upstream. Considering that maintaining all those components at low temperature is a vital procedure, an appropriate method as the objective of this study is to be investigated.

Film Cooling is one of the effective methods to achieve this objective in which impressing mass flux ratio is the key to raise efficiency of this method. However, in this study it is shown that augmentation of the blowing ratio, as cited in previous researches, is not that much suitable to gain the highest possible efficiency; in other words, the coolant is less likely to remain attached to the surface to protect the critical components. This study shows that changes in the structure of the cylindrical cooling holes are the best way to achieve higher cooling efficiency in the combustor.

According to the literature, row compound cooling holes impress the film cooling performance more effectively compared to individual cases. Since, the structure of cylindrical cooling holes placement at the end of combustor simulator and the effects of different alignment angles of row cylindrical cooling holes have great impact on cooling efficiency so, many researches have been focused on these factors. Vakil and Thole [1], Kianpour et al. [2], Azzi and Jurban [3] and Rozati and Danesh Tafti [4] have presented experimental and computational results of the combustor simulator. Furthermore, Stitzel and Thole [5] indicated that dilution jet injection is the dominant feature at the combustor exit, while with no dilution, the exit profile was relatively uniform with a high temperature and low total pressure flow in the mainstream. Therefore the objective of present study is to investigate

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film cooling effectiveness variation resulted from different arrangements of cooling holes. For validation, the result of this study is compared with that of Vakil and Thole [1].

2.0 METHODOLOGY

In this study a three-dimensional representation of a Pratt and Whitney engine was modelled and analyzed. The schematic of the combustor is that shown in Fig. 1. The final combustor simulator design length, width and inlet height respectively are 156.9*cm*, 111.8*cm* and 99.1*cm*. The contraction angle is 15.8 degree and begins at $x = 79.8\,cm$. The inlet and outlet cross sectional area are 1.11 m^2 and 0.62 m^2.

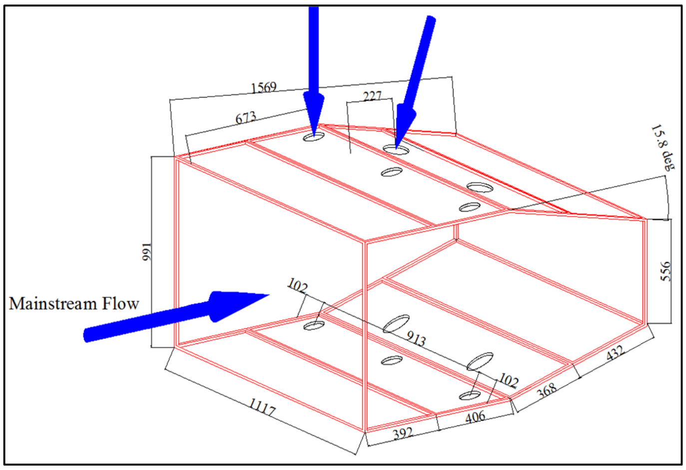

Figure 1: 3-D view of the combustor simulator

The combustor simulator included four film-cooled panels. The starting point of these panels is approximately at 1.6*m* upstream of the turbine vanes. The length of panels are 39.2, 40.6, 36.8 and 43.2 *cm* respectively. The low thermal conductivity of combustor panels allowed for adiabatic surface assumption. Two different rows of dilution holes were considered within the second and third panels. These dilution rows are located at 0.67*m* and 0.90*m* downstream of the combustor liner panels' beginning. The diameter of the first and second row of dilution holes are 8.5*cm* and 12.1*cm* respectively.

In this study, the combustor included two configurations of cooling holes. The diameter of the film cooling holes is 0.76*cm* drilled at 30 degree of angle tangent to the horizontal surface. The length of each film cooling hole in the baseline is 2.5*cm* and for the second case accomplished row compound cooling holes are with alignment angle of 30 degree. Film cooling effectiveness (η) in the combustor was measured along the specific measurement planes as shown in Fig. 2. The measurement planes of 0p, 1p, 2p and 3p are located in pitch wise direction. The numerical method has been considered as steady, compressible turbulent flow by means of the RNG k-ε turbulent model of the Navier-Stokes equations expressed as follows;

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}\frac{dx}{dt}+\frac{\partial \rho}{\partial y}\frac{dy}{dt}+\frac{\partial \rho}{\partial z}\frac{dz}{dt}=-\rho(\nabla .V) \qquad (1)$$

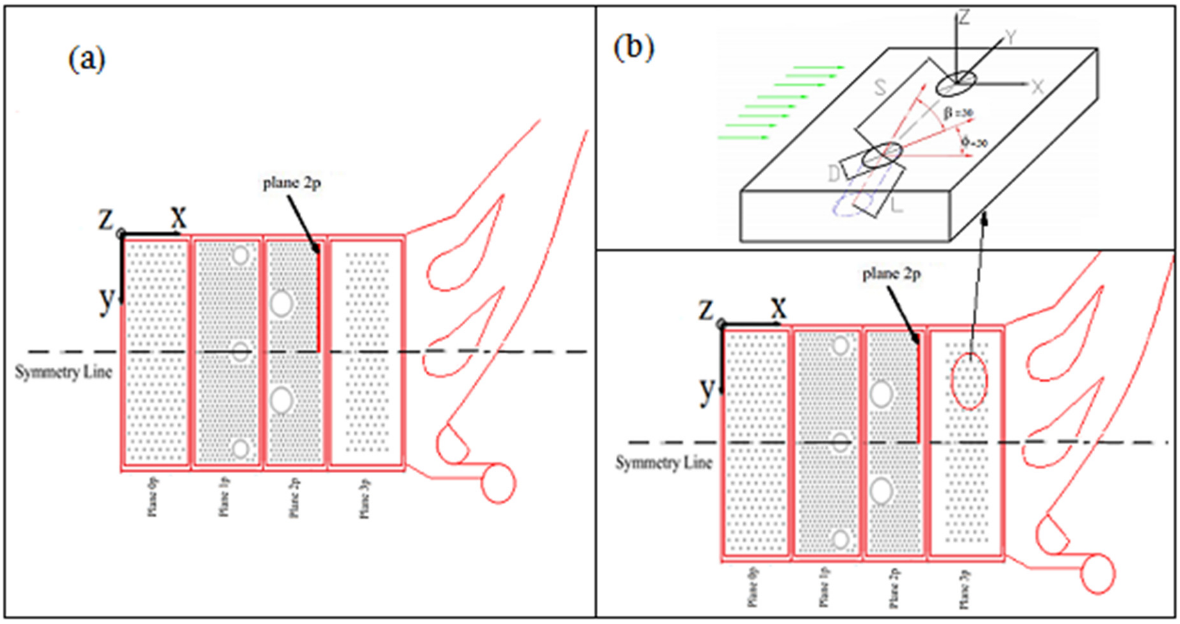

Figure 2: Location of the measurement planes (a) baseline case (b) compound case

Momentum equation,

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}=(\rho U_i U_j)=-\frac{\partial P}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_i}+\rho g_i+\vec{F}_1 \qquad (2)$$

Energy equation,

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_j}=(U_i(\rho E+P))=\frac{\partial}{\partial x_i}\left(K_{eff}\frac{\partial T}{\partial x_i}-\sum_j h_j J_j+u_j(\tau_{ij})_{erf}\right)+S_h \qquad (3)$$

RNG $k-\varepsilon$ equation,

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} \qquad (5)$$

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and film cooling effectiveness is defined as below,

$$\eta = \frac{T - T_\infty}{T_C - T_\infty} \tag{6}$$

3.0 FINDINGS AND DISCUSSION

Fig. 3 shows a comparison of film cooling effectiveness for baseline case between the current study and experimental results by Vakil and Thole [1] at high blowing ratio of $BR = 3.18$ for plane 2p at $y/W = 0.25$. According to Eqn. 7, the deviation was equal to 14.56% when compared to Ref. [1].

$$\%Diff = \frac{\sum_{i=1}^{n} \frac{x_i - x_{i,benchmark}}{x_{i,benchmark}}}{n} \times 100 \tag{7}$$

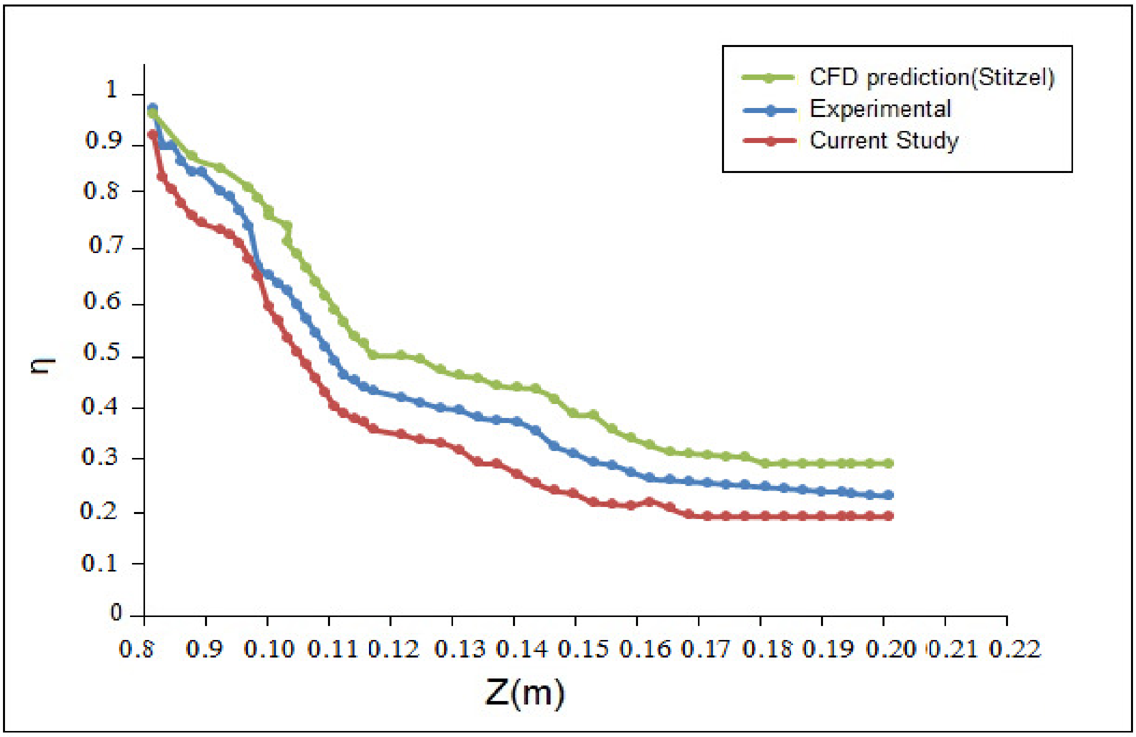

Figure 3: Comparison of film cooling effectiveness for plane 2p along $y/W = 0.25$.

Fig. 4 illustrates the film cooling effectiveness in plane 2p at blowing ratio of $BR = 3.18$. As can be induced, the center of the dilution jet is reasonably centered about the corners of this observation plane as the jet surges up. Note that jet spreading rate is slightly higher for $y = 10cm$ and $y = 50cm$ that can be due to the jet's interaction with its top row. Also,

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contrary to the baseline, it is slightly hotter $(0\langle \eta \langle 0.05)$ for the compound case with alignment angles of 30 degree in the position of $14cm\langle y \langle 52cm$ and $8cm\langle z \langle 10cm$. However, compared to another case, this type of compound cooling holes, adjacent to end wall surfaces, performs more efficiently.

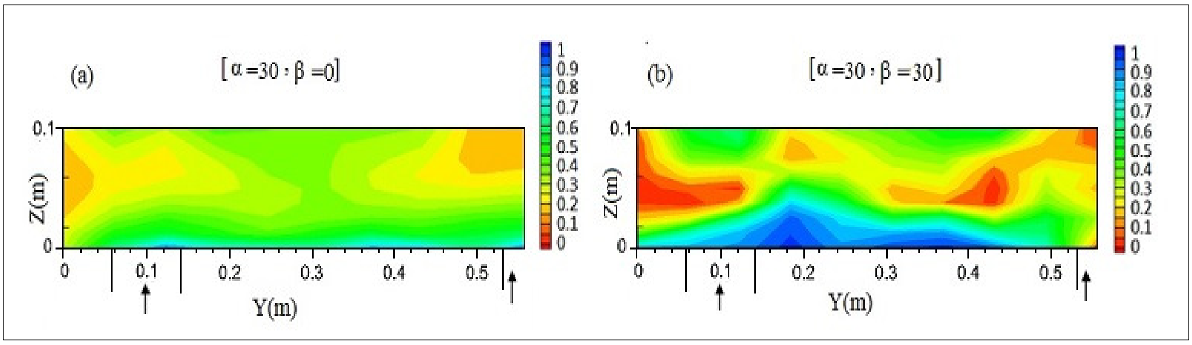

Figure 4: Illustrative of normalized temperature contours for plane 2p

4.0 CONCLUSION

The end wall of a combustion chamber can be damaged by the hot gases. Since maintaining all the components at low temperature is an important fact thus, improvement of the current techniques has been always at center of attention. In this research a three-dimensional representation of a real Pratt and Whitney engine was simulated to analyze the effects of cylindrical and compound cooling holes with alignment angle of 30 degree at $BR = 3.18$ on film cooling effectiveness at the end wall of combustor simulator. It was concluded that by utilizing compound cooling holes the film cooling layer considerably developed. In addition the middle of plane 2p demonstrated intensive penetration of coolant and a thick film cooling layer created in the compound configuration case. The findings of the study declared that with using the row trenched holes near the end wall surface, film cooling effectiveness increases three times compared to the cooling performance of baseline case.

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