An Evaluation of the Performance of a Novel Film Cooling Holes applied to Gas Turbine Blades

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ABSTRACT

Modern gas turbine engines require a sophisticated cooling system design to achieve higher power output and efficiency. The present work aims to improve the film cooling effectiveness using a novel configuration based on an enlarged spanwise cooling hole. First, the numerical results are compared with experimental data of Fan-Shaped Holes (FSHs), which are widely used as a design in turbine blades. The proposed shape is designed to enhance the efficiency of the coolant jet across all cooling areas. The main operating parameters applied were a density ratio of 1.7 and a blowing ratio ranging from 0.5 to 2.5. The simulations were performed using three-dimensional Reynolds-averaged Navier–Stokes (RANS) analysis with the SST k-ω turbulence model. The comparison showed that the proposed design numerical results closely match the experimental data for FSHs. At lower blowing ratios (0.5), the proposed Diffused Shaped Hole (DSH) achieves higher area-averaged film cooling effectiveness than the FSH while maintaining the same coolant usage. At higher blowing ratios, the DSH provides a more uniform distribution and an improved cooling effectiveness on the film than the FSH.

Keywords-blowing ratio; cooling effectiveness; fan-shaped hole; novel diffussed shaped hole; SST k-ω model

I. INTRODUCTION

The development of a new generation of high-performance aircraft turbine jet engines requires gas turbines to operate at very high turbine rotor inlet gas temperatures. Consequently, innovative cooling techniques for gas turbine blades are needed to handle the high temperatures. The optimal film cooling structure is a continuous slot that uniformly distributes coolant over the blade surface while minimizing the coolant-blowing ratio. The cooling techniques currently available are the internal and external cooling methods. Several studies [1-5] have focused on optimizing film cooling system designs and developing materials with exceptional resistance to hot gases to enhance cooling efficiency while minimizing coolant usage. Authors in [6] demonstrated that the material CM247LC had more suitable characteristics for the manufacturing of gas turbine blades. Authors in [7-11] analyzed film cooling jets in crossflow at a compound angle, revealing that key geometric parameters of FSHs significantly influence cooling efficiency. Authors in [12] found that coolant span coverage can be substantially increased while reducing jet penetration. Additionally, authors in [13-15] compared two different FSH configurations in terms of film cooling effectiveness and heat transfer coefficients. Their findings indicate that a laid-back FSH, diffusing in both spanwise and streamwise directions, exhibits superior thermal performance compared to holes diffusing only in the spanwise direction, particularly at high blowing ratios. Authors in [16] studied shaped holes with equal area ratios and observed similar discharge coefficients. They reported that higher blowing ratios and effective exit widths ensure smooth coolant flow without detachment. Authors in [17] demonstrated that a FSH using a Kriging surrogate model and a multi-island genetic algorithm, achieved a 70 % enhancement in cooling effectiveness over the baseline design.

Authors in [18] used machine learning and genetic algorithms to optimize laid-back FSHs on the blunt body leading-edge, revealing the sensitivity of cooling effectiveness to structural parameters. Authors in [19] exhibited that a short hole can enhance jet penetration and favor the interaction between the mainstream flow and the cooling air. The investigation in [20] revealed that film cooling effectiveness significantly improves when the range of length-to-diameter ratio is below 5 and the blowing ratio is between 0.5 and 1.0.

In this study, a novel cooling hole configuration was proposed. The new design expands the hole into a diffused shape in both the spanwise and streamwise directions, addressing the key limitation of FSHs, which is the loss of film cooling efficiency in the central region of the main flow.

II. GOVERNING EQUATION AND SIMULATION

The computations are performed using ANSYS CFX, which incorporates conjugate heat transfer capability. Figure 1 illustrates the film cooling process configuration, while Figure 2 describes both the FSH and the novel DSH configurations. The leading-edge region of the turbine blade is cooled down via three cooling mechanisms, as portrayed in Figure 3, which also describes several boundary conditions used in this study. The adiabatic and no-slip conditions are applied on the walls and a constant mass flow rate is obtained/is set at the inlet of the coolant channel. The total pressure at the inlet of the hot gas and the cold flow are set to 100 Pa and 400 Pa, respectively. The static pressure at the outlet of the hot channel is set as 93 Pa and 500 Pa at the outlet of the cold channel. The temperature of the hot gas and the coolant are set to 540 K and 290 K, respectively, and the density ratio is set at 1.75. The periodic boundary condition is adopted at the side walls of the main channel. Convergence was attained when the Root-Mean-Squared (RMS) residual values of all flow parameters fell below 10^{-5}.

Backside and forced convective cooling are usually characterized as internal convective cooling and film cooling, taking place on the external surface after the cooling fluid is ejected. The cooling holes in this study maintain identical proportions, regarding the cylindrical portion's diameter. As described in [9], the film cooling effectiveness can be defined with the following equations (1-3)/by:

The film cooling effectiveness ETA:

$$ETA = \frac{T_g - T_{aw}}{T_g - T_{co}} \tag{1}$$

T_g: Temperature of hot gas.

T_{aw}: Temperature adiabatic of the wall.

T_{co}: Temperature at hole exit conditions.

The blowing ratio is defined by:

$$G = \frac{U_c \rho_c}{U_h \rho_h} \tag{2}$$

where U_c, U_h, and ρ_c, ρ_h are the velocities and the density of coolant and hot flow, respectively.

The quantitative description of spatially averaged film-cooling effectiveness is computed over an area that is six diameters in width and ten diameters in length in the streamwise direction, and is calculated as:

$$\overline{ETA} = \frac{1}{6D}\int_{-3D}^{3D} ETA\, ds \tag{3}$$

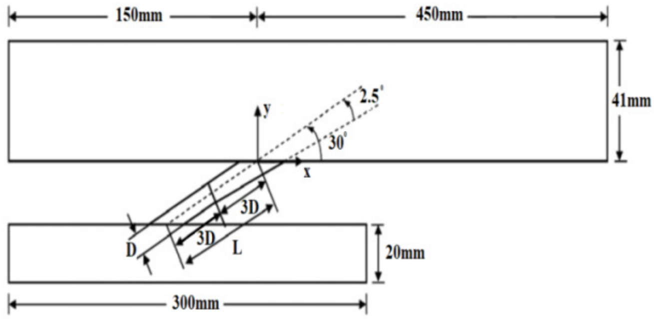

Fig. 1. Numerical geometry of FSH.

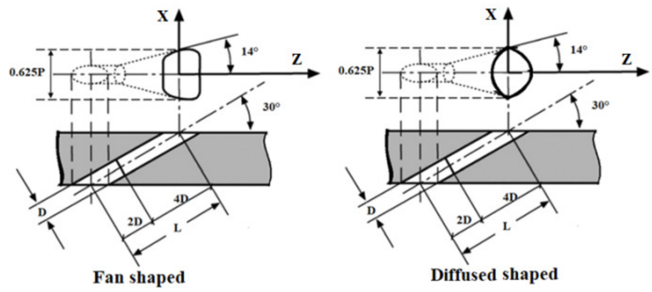

Fig. 2. Configuration of numerical study.

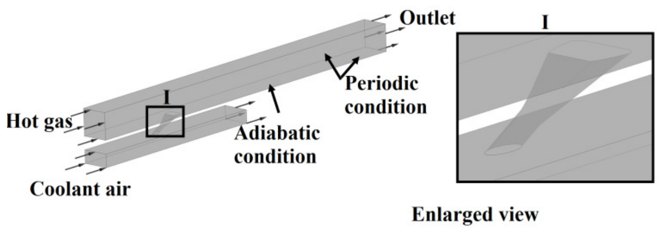

Fig. 3. Computational domain.

III. NUMERICAL ANALYSIS

The Computational Fluid Dynamics (CFD) tools are used to simulate the performance of the film cooling process. Compared to experimental methods, numerical simulation provides access to parameters that are difficult to measure in complex experiments. In the process of turbine blade design, he numerical simulation can optimize the hot section components of engines and explore cooling techniques with higher efficiency. The three-dimensional steady incompressible RANS equations were solved utilizing ANSYS CFX, with turbulence modeling based on the SST k-ω model, described in [21], and coupled with the Gamma-Theta transition model. The governing equations are:

Continuity equations:

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{4}$$

Momentum equation:

$$\rho \frac{\partial (u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) - \partial\overline{\rho u_i' u_j'}\right] \tag{5}$$

where $\overline{\rho u_i' u_j'}$ represents the Reynolds stresses.

Energy equation:

$$\rho \frac{\partial (C_p u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i} - \rho C_p \overline{u_i' T'}\right) \tag{6}$$

where $\rho C_p \overline{u_i' T'}$ represents the turbulent heat fluxes.

An unstructured mesh of the computational domain is used, with Figure 4 depicting the grid structure within the blade domain. The grid was densely refined in regions of high film cooling interaction and blade-wall heat transfer to resolve high-velocity gradients and improve coolant flow accuracy. Additionally, local refinement was applied at the hole exits to enhance the precision of cooling and flow characteristics in this region. All the boundary conditions and the computational domain have been determined according to the results of the experimental study in [8].

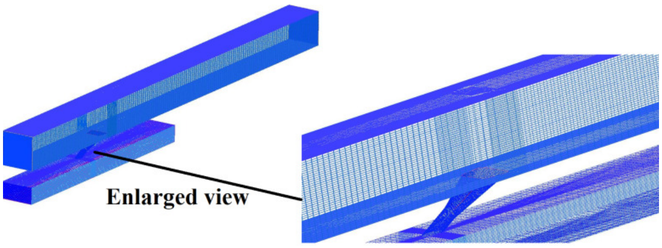

Fig. 4. Grid system for the shaped hole.

IV. VALIDATION

The precision of numerical simulations is validated through a comparison of the computational results for the FSH at four different blowing ratios with the experimental data in [8]. Figure 5 indicates that the computational results were consistent with the experimental results. Additionally, the DSH demonstrates improved film cooling effectiveness across all blowing ratios, providing enhanced coolant flow coverage in the leading-edge region.

To assess grid dependency, three different grids were tested by comparing both velocity profiles at X/D = 0 and Z/D = 1, and laterally averaged film-cooling effectiveness at the centerline, as displayed in Figure 6. In several cases, an adaptive grid refinement was applied around the film holes. The results obtained from 0.8 million and 1 million cells were relatively consistent, whereas the 0.5 million cell grid produced slightly deviant results. Based on these findings, the 0.8 million-cell grid was selected as the optimal configuration for the current simulation.

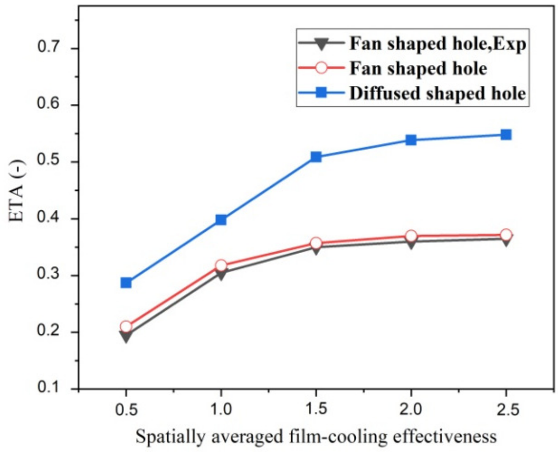

Fig. 5. Comparison of spatially averaged film-cooling effectiveness.

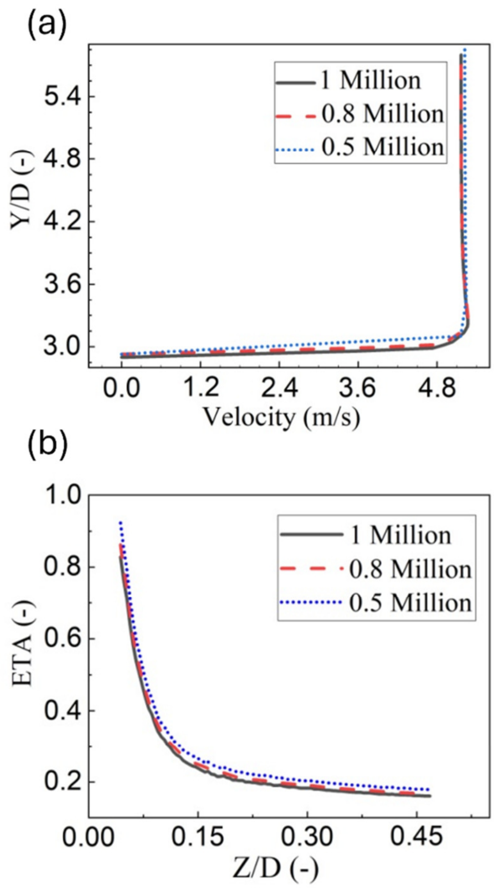

Fig. 6. The grid-dependency test: (a) velocity in the y-direction (X/D=0, Z/D=1) and (b) laterally averaged film-cooling effectiveness.

V. RESULTS AND DISCUSSION

Figure 7 presents the contours of the velocities in the y-direction (velocity V) and the x-direction (velocity U) for each hole geometry at the exit holes. Figure 7a shows the comparison of the velocity profiles at the FSH and DSH, with the highest momentum in the y-direction being produced at the extremities of the hole from the FSH. On the contrary, the DSH exhibits a more uniform velocity distribution, with higher values being concentrated at the backside of the hole. However, the coolant exiting from the hole enhances penetration into the mainstream hot gas and consequently provides lower film cooling effectiveness. Nevertheless, in Figure 7b, the DSH shows a higher velocity component in the x-direction (velocity U), leading to better lateral coolant spreading. This finding is also confirmed in Figure 8, which provides additional insights into the enhanced mainstream velocity U of the DSH compared to FSH. The contours exhibit the detailed adiabatic distribution of laterally film cooling effectiveness along the streamwise direction (z-direction) wall for both geometries at different blowing ratios (G=0.5, 1, 1.5, 2, and 2.5). As the blowing ratio increases, the coolant jet penetration into the mainstream increases, leading to the coolant lift-off phenomenon at high blowing ratios near the exit hole. Regarding the FSH, a detachment of the coolant jet from the wall is observed at the centerline of the cooling surface, resulting in weakened cooling efficiency, but the lateral average film cooling effectiveness remains enhanced. On the other hand, the DSH provides more uniform cooling effectiveness across all blowing ratios, especially at higher blowing ratios, thereby improving the thermal protection of the surface

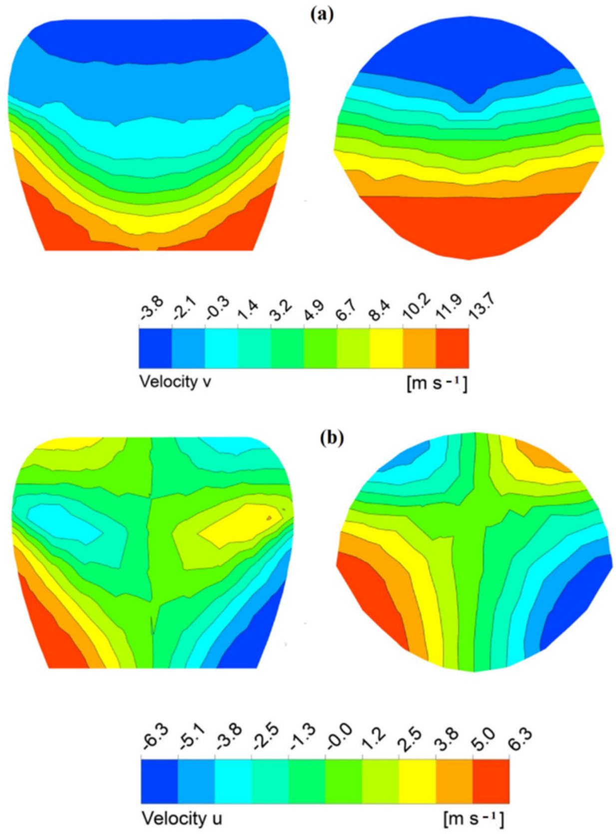

Fig. 7. Velocity contours at the hole exits of the FSH and DSH (G=2.5): (a) velocity component in the y-direction (V), (b) velocity component in the x-direction (U).

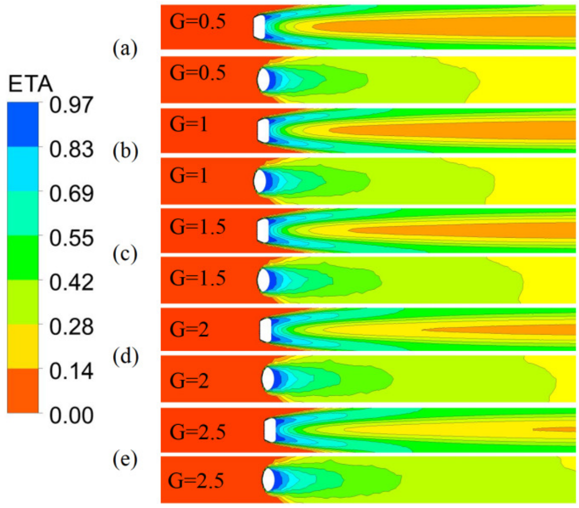

Fig. 8. Comparison of local film cooling effectiveness of FSH and the DSH at: (a) G=0.5, (b) G=1, (c) G=1.5, (d) G=2, and (e) G=2.5.

This remark is further validated in Figure 9, which depicts a noticeable improvement in film cooling effectiveness across all blowing ratios, with DSH achieving better efficiency compared to the FSH.

Figure 10 illustrates the streamlines of the coolant flow at a blowing ratio of G=2.5, showing the distribution of the coolant jet on the inside and the outside of both configurations. The uniform distribution of coolant jets was efficiently generated inside and outside the DSH, and a homogeneous distribution was reached in the ejection region. In contrast, the FSH exhibits a significant separation bubble in the central ejection region, which directly influences coolant jet efficiency. The extent of this separation is strongly dependent on the hole geometry and plays a crucial role in determining cooling performance.

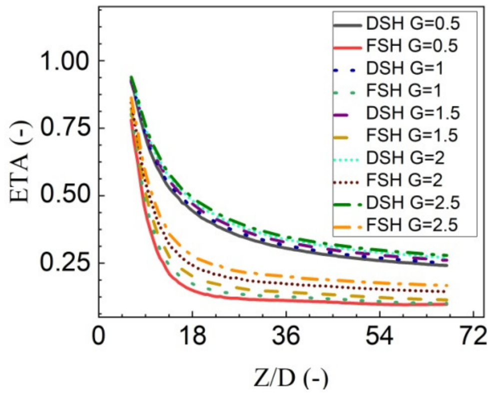

Fig. 9. Comparison of laterally averaged film cooling effectiveness of DSH and FSH at all ranges of blowing ratios.

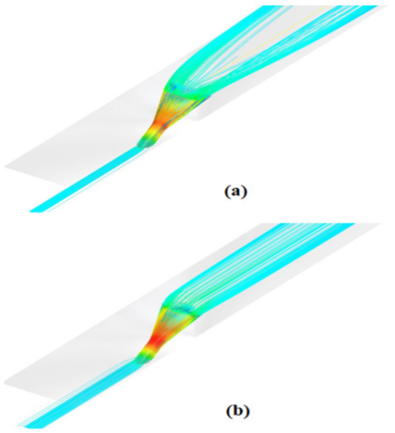

Fig. 10. Streamlines of the coolant (G=2.5): (a) FSH and (b) DSH.

VI. CONCLUSION

One of the major commonly encountered challenges in film cooling systems is jet detachment, which occurs when the coolant jet penetrates the mainstream flow. Several factors contribute to this phenomenon, such as hole inclination, the shape of the hole at the ejection zone, the discontinuity of film cooling in the spanwise direction, and the non-uniform temperature distribution at the leading-edge. Extensive research has focused on mitigating these issues. The present study contributes to these advancements by proposing enlarging the hole geometry in both the spanwise and streamwise directions, optimizing a more effective coolant distribution.

This study numerically investigates a novel film-cooling hole design, named Diffused Shaped Hole (DSH), and compares its performance against the conventional Fan-Shaped Hole (FSH), which is widely used in current turbine blade cooling systems. The three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations coupled with the SST k-ω turbulence model were used for the simulation with a density ratio of 1.7 across a blowing ratio range of 0.5-2.5. Initially, the numerical results for the FSH were validated against the experimental data, demonstrating excellent agreement between the simulations and experimental findings. Then, the simulated FSH results were compared with the proposed DSH design. At a blowing ratio of 0.5, the DSH exhibits a more uniform and homogeneous cooling distribution compared to the conventional FSH. However, as the blowing ratio increases, the DSH demonstrates superior film cooling effectiveness, particularly in enhancing coolant spreading at the centerline and improving film cooling recovery. Additionally, the results indicate that lateral expansion at the leading-edge plays a crucial role in enhancing cooling performance by promoting better surface coverage. The numerical simulations confirm that the coolant film generated by the DSH diffuses more uniformly in the streamwise direction, maintaining better surface attachment and significantly reducing lift-off phenomena. Overall, the DSH achieves a significantly higher level of film cooling effectiveness than the FSH, making it a promising alternative for improving turbine blade cooling efficiency.

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