CFD Analysis of Gas Turbine Blade Cooling with Different Materials and Cooling Hole Configurations

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CFD Analysis of Gas Turbine Blade Cooling with Different Materials and Cooling Hole Configurations

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Abstract. The cooling of turbine blades is a must to run the gas turbine engine smoothly and without threat, especially when it operates at high temperatures. The elevated temperature can lead to the breakdown of turbine blades because of excessive thermal stress when they rotate at very high rpm. This research uses the NACA 6409 airfoil design to conduct an extensive Computational Fluid Dynamics (CFD) investigation on the cooling of turbine blades. Using several configurations of circular cooling holes along the blade span - 4, 6, and 8 inline and staggered pattern, the study evaluates the cooling effectiveness of blades constructed of Chromium Steel, Haynes 188, and Inconel 718. By running detailed simulations using commercial CFD software, this experiment investigated the thermal behavior and heat transfer characteristics of these different models, and the most effective cooling scheme was identified to enhance blade performance in high temperature operational environments.

***Keywords**:* Cooling, Turbine Blades, CFD, Heat Transfer, Inline, and Staggered.

INTRODUCTION

The turbine of a gas turbine engine plays a significant function by converting energy from combustion. The fuel and air are burned in the combustion chamber of the engine, thereby raising the temperature and pressure of the gases. These highly pressurized gases cause the turbine's blades to rotate, which then drives other important parts like the compressor. This process is important to propel the engine for generating the necessary thrust, but it leads to the production of much heat, which can cause serious damage. If it is not handled properly, the extreme heat can make the metal parts wear out, turn to rust, and finally fall apart. For a turbine to work well and last a long, it needs good cooling systems in place.

To deal with the issue of excessive heat, a variety of cooling methods are put into practice. In the approach known as film cooling, a shield of cooler air is formed right above the turbine blades to protect them from unrestrained heat. Another method involves creating paths inside the blades for cool air to move around, which helps to dissipate heat. The paths can be circular or elliptical and are distributed near the entire surface of the blade. Using jet impingement cooling means shooting cool air at certain areas of the turbine so they don't get too hot. Moreover, the creation of superalloy materials has the capability of withstanding extreme temperatures without significant deterioration. [1]

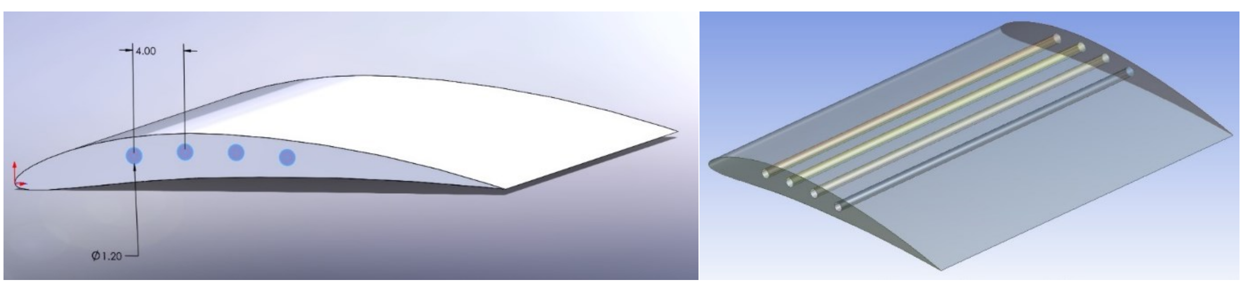
Several studies have been performed by the researchers on the cooling of turbine blade. Pawar et al. [2] conducted a numerical study on convection cooling for gas turbine blades, comparing square, triangular, and semi-circular hole profiles using CFD software. From the result it was found that the 17 holes in square shape provided the highest adiabatic film cooling efficiency ($\eta_{ad} \approx 0.487$) at 1400°C. Increasing the number of holes, particularly near the trailing edge and on pressure and suction sides, improved the overall heat transfer and reduced the surface temperature. Mathew et al. [3] evaluated the performance of RKE and SST turbulence models in predicting film cooling on a turbine blade leading edge, using CFD and experimental comparisons. Neither model accurately predicted adiabatic effectiveness and thermal fields, particularly at the stagnation line. The findings suggested the limitations of RANS models, recommending Unsteady-RANS or LES for improved accuracy. Chi et al. [4] introduced a multi-dimensional platform for air-cooled turbine blade design, combining 1D flow network models for schematic design and ANSYS CFX-based conjugate heat transfer simulations for detailed design. The platform included automated parametric design and mesh generation tools, significantly improving efficiency. Their future work focused on enhancing solver accuracy, mesh quality, and expanding mesh generation capabilities for various cooling structures. Sciubba [5] presented a simple, analytical lumped thermodynamic model for estimating turbine blade cooling requirements, providing rapid, first-order predictions with minimal computational cost. Despite neglecting 3D thermal gradients and detailed geometry, the model showed satisfactory accuracy compared to more complex simulations. It served as a practical tool for preliminary design and efficiency assessments in gas turbines. Andreini et al. [6] investigated the impact of coolant mass flow rates on flow dynamics within a turbine stator well using CFD simulations. Results showed that coolant flow significantly influenced recirculation and vortex formation in the first cavity, while the second cavity remained largely unaffected. Increased coolant mass flow reduced tangential momentum losses in the main annulus, affecting secondary flow development near turbine hub walls. Luabi et al. [7] proposed elliptical cooling holes to enhance heat transfer in gas turbine blades, analyzing various aspect ratios and hole distributions. Among the three new models tested, model-4, with an aspect ratio of 2 (a = 2, b = 1), optimally reduced the blade's trailing edge temperature by 24% compared to the model-1 which was already installed. CFD analysis confirmed that increasing the number of cooling holes effectively lowers blade temperature, depending on their placement.

Although various studies have been conducted on turbine blade cooling, limited research has focused on the NACA 6409 airfoil. This paper illustrates convective cooling through the creation of internal passages. Cold air at high velocity has been flown throughout the blade to efficiently remove heat generated during turbine operation. Three different types of alloys have been used as blade materials, with different numbers of holes in inline and staggered positions. The temperature drop and heat transfer rate of these arrangements were compared, and the best configuration was chosen according to the highest heat transfer rate.

METHODOLOGY

Airfoil Geometry

From 'Airfoil Tools', the coordinates of the NACA 6409 airfoil have been taken, and the geometry of the turbine blade was designed using 'SolidWorks'. Then the designed blade was imported into 'Ansys' for CFD analysis of the heat transfer and the reduction of temperature over the blade. A structured meshing was done to the geometry for a more accurate result. An appropriate solver has been selected for heat transfer simulations, and the results were analyzed to obtain the optimum design.



(a) (b)

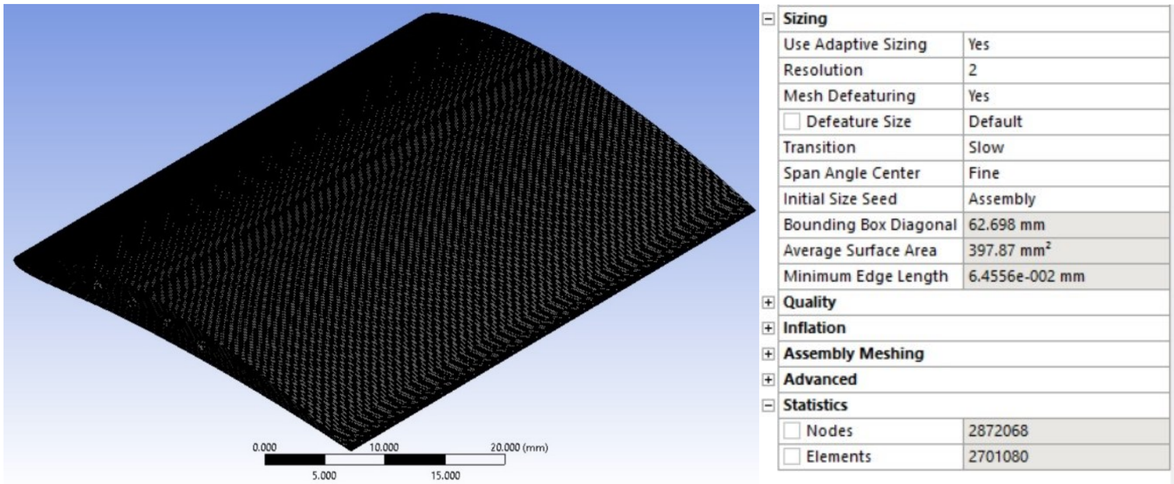
Figure 1. Geometry (a) CAD Design in 'SOLIDWORKS' (4 inline holes) and (b) Design Imported in 'ANSYS'

The specifications of the blade are given below: -

Table 1. Blade Specifications

Airfoil	NACA 6409
Blade Span	195 mm
Chord Length	40 mm
Hole Diameter	1.2 mm
Distance between two holes	4 mm

Meshing



(a) (b)

Figure 2. (a) Meshing (b) Details of the Mesh

Solution Method

The k-ε standard energy model has been employed to improve wall treatment and enable convective heat transfer. A pressure-velocity coupling method, along with a pressure-based solver, was employed to solve equations on a significantly skewed mesh within a comparable number of iterations needed for a more evenly distributed mesh. The computational conditions and flow specifications to solve the equations are given below: -

Table 2. Computational Conditions and Flow Specifications

Solution Model	k-ε standard
Scheme	PISO (Pressure-Implicit with Splitting of Operators)
Gradient	Least Squares Cell Based
Solver	Pressure Based
Convective Heat Transfer Coefficient of outer surface	2712 W/m^2 K
of blade	1250 K
Temperature of outer surface of blade	303 K
Temperature of cold air	100 m/s

Grid Independence Test

Grid independence ensures that simulation outcomes remain consistent, regardless of the computational grid's size or density. This test is important in computational fluid dynamics (CFD), where the accuracy of the results is heavily dependent on the discretization quality of the geometry. The purpose is to reach a point where further grid refinement leads to negligible changes in the results, indicating that the simulation outcomes are insensitive to variations in grid resolution. This practice is essential for determining converging mesh value that provides a balance between accuracy and computational efficiency, thereby avoiding unnecessary computational expense.

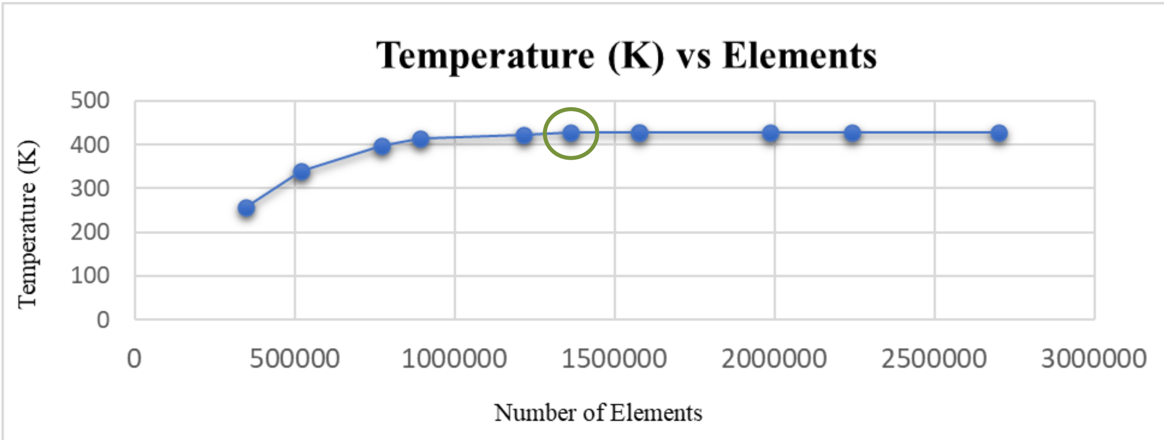


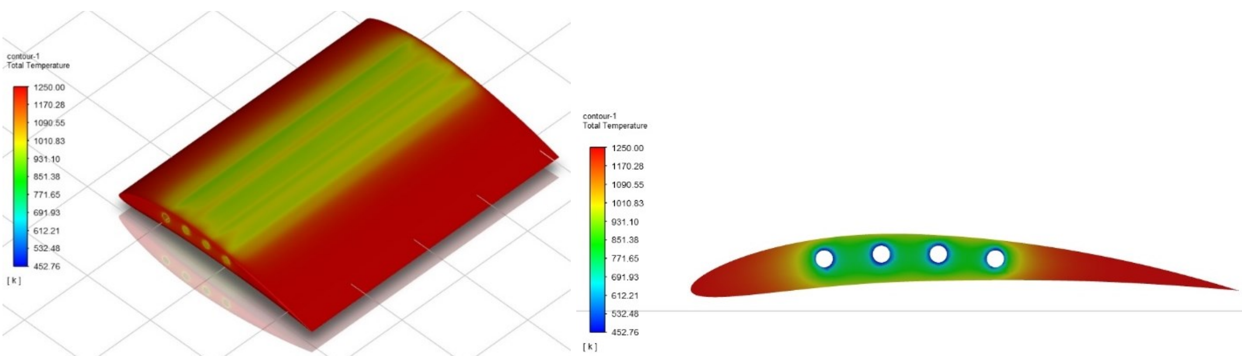
Figure 3. Grid Independence Test

From figure 3, it is observed that the result variation is not significant after around 1,360,000 elements. Hence, the elements after that can be omitted since this mesh size will result in less computational runtime compared to a finer mesh and also minimize computational memory.

RESULT AND DISCUSSION

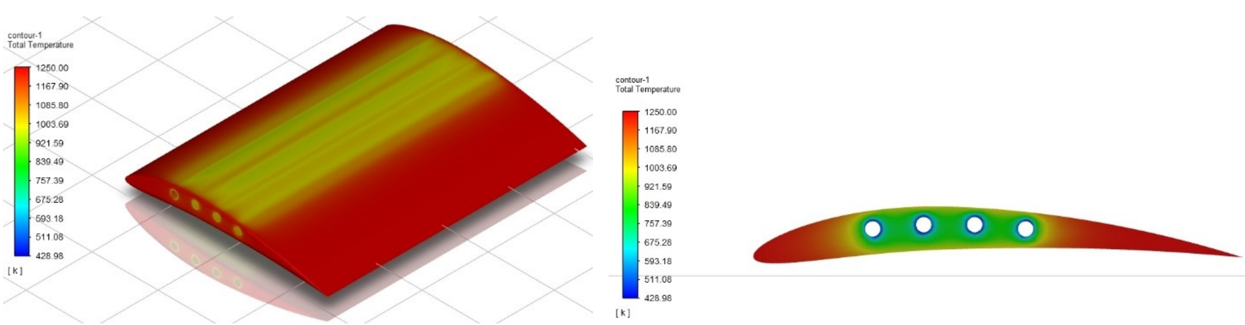
Temperature Contour

4 Inline Holes Configuration



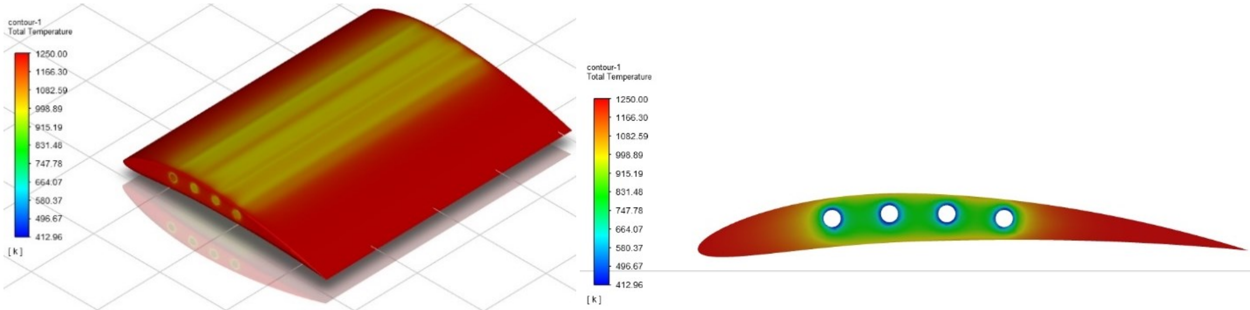
(a) (b)

Figure 4. Temperature Contour of 'Chromium Steel' (a) Isometric View (b) Cross-sectional View



(a) (b)

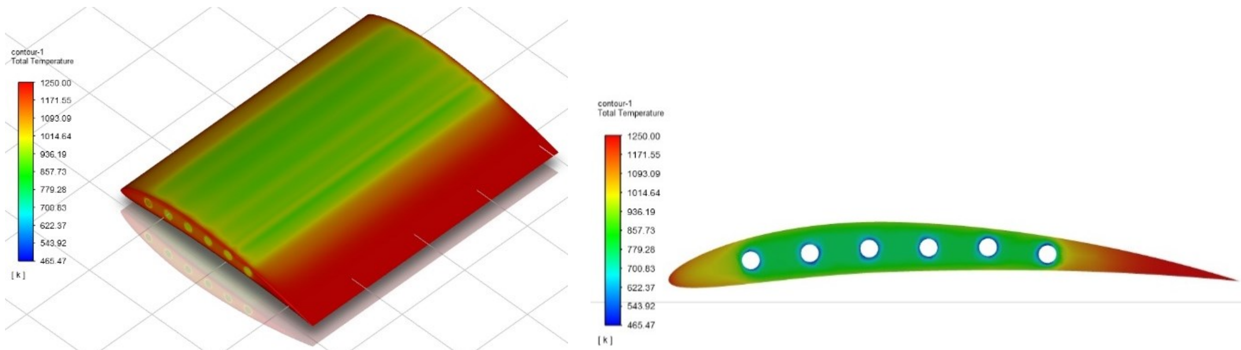
Figure 5. Temperature Contour of 'Haynes 188' (a) Isometric View (b) Cross-sectional View



(a) (b)

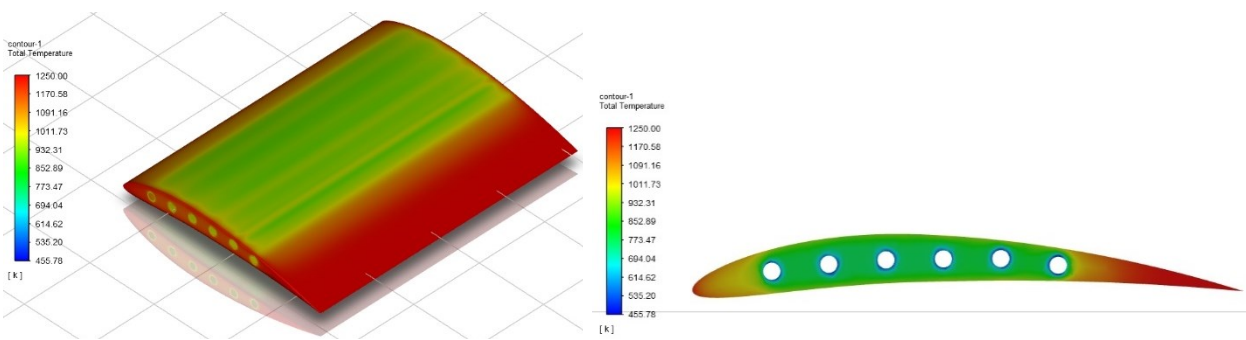
Figure 6. Temperature Contour of 'Inconel 718' (a) Isometric View (b) Cross-sectional View

6 Inline Holes Configuration



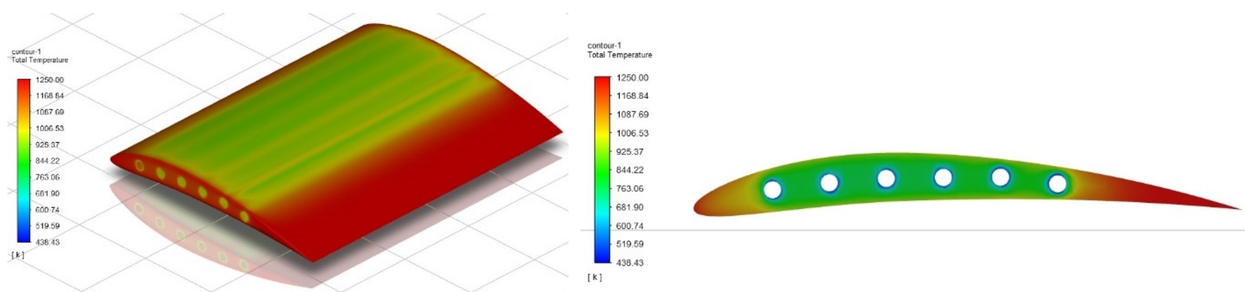
(a) (b)

Figure 7. Temperature Contour of 'Chromium Steel' (a) Isometric View (b) Cross-sectional View



(a) (b)

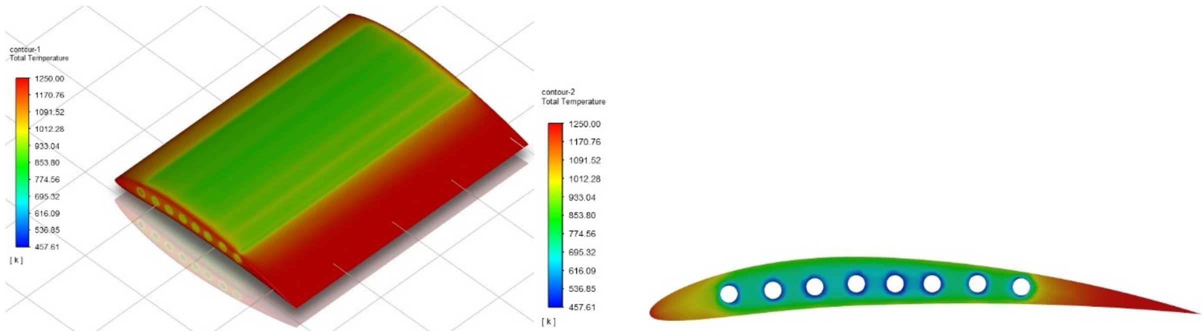
Figure 8. Temperature Contour of 'Haynes 188' (a) Isometric View (b) Cross-sectional View



(a) (b)

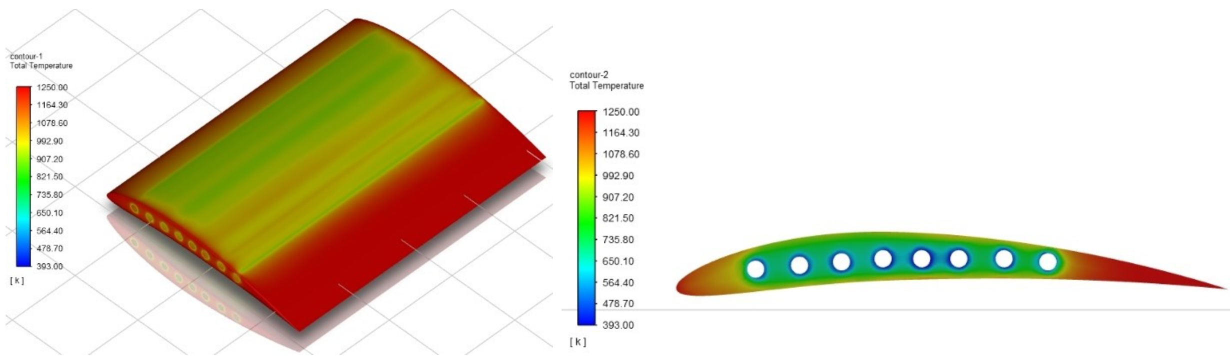
Figure 9. Temperature Contour of 'Inconel 718' (a) Isometric View (b) Cross-sectional View

8 Inline Holes Configuration



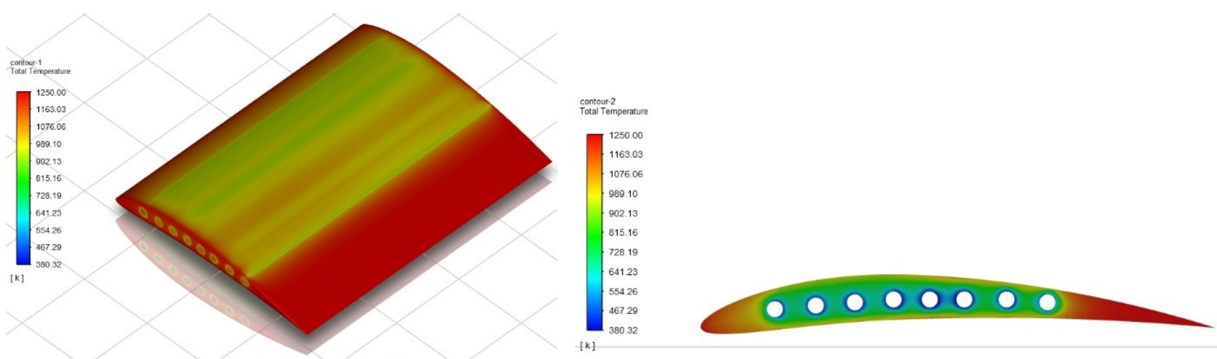
(a) (b)

Figure 10. Temperature Contour of 'Chromium Steel' (a) Isometric View (b) Cross-sectional View



(a) (b)

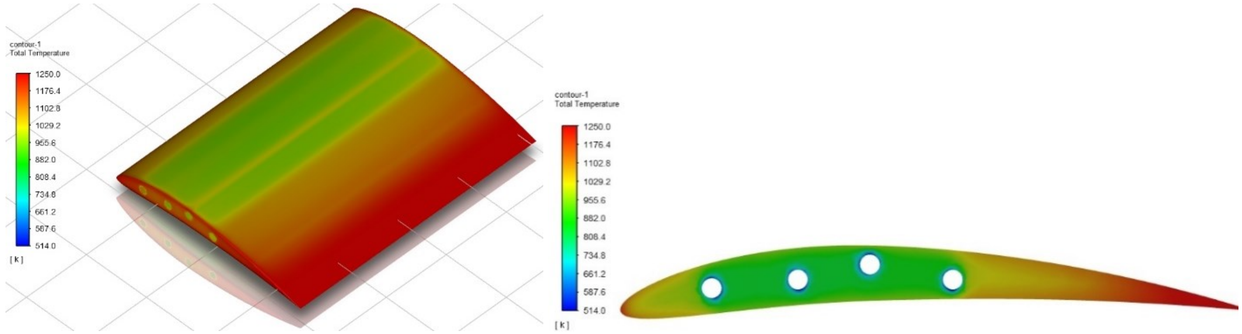
Figure 11. Temperature Contour of 'Haynes 188' (a) Isometric View (b) Cross-sectional View



(a) (b)

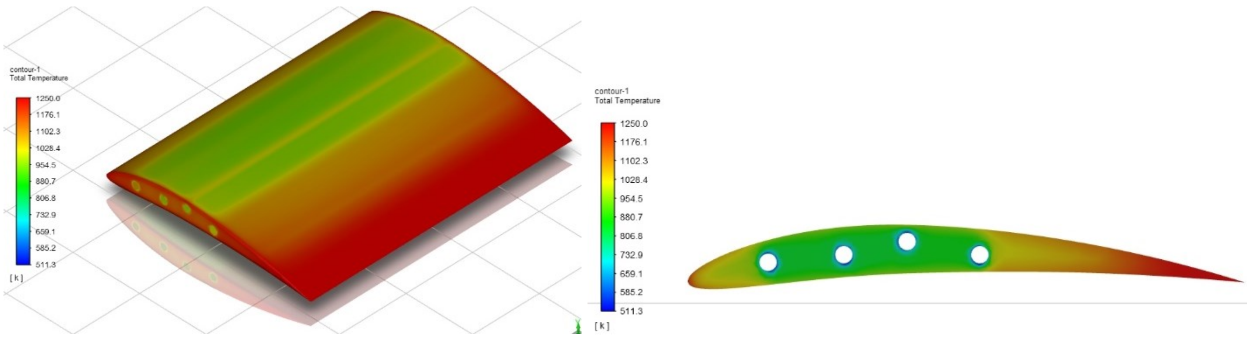
Figure 12. Temperature Contour of 'Inconel 718' (a) Isometric View (b) Cross-sectional View

4 Staggered Holes Configuration



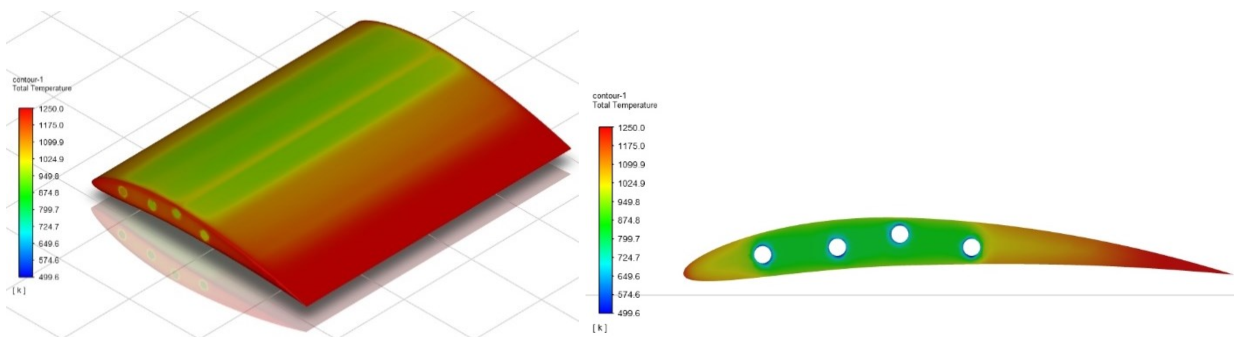
(a) (b)

Figure 13. Temperature Contour of 'Chromium Steel' (a) Isometric View (b) Cross-sectional View



(a) (b)

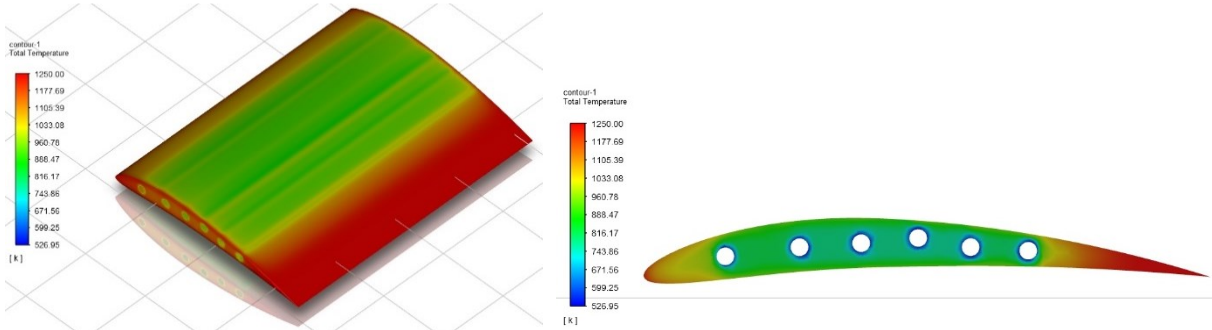
Figure 14. Temperature Contour of 'Haynes 188' (a) Isometric View (b) Cross-sectional View



(a) (b)

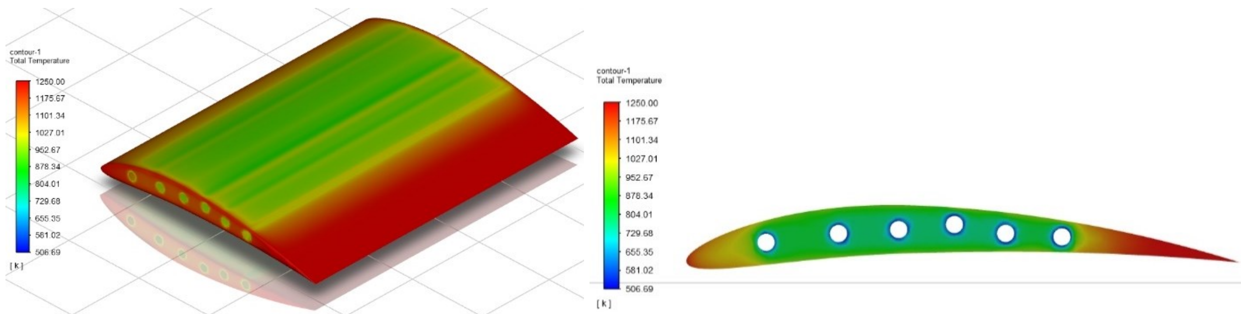
Figure 15. Temperature Contour of 'Inconel 718' (a) Isometric View (b) Cross-sectional View

6 Staggered Holes Configuration



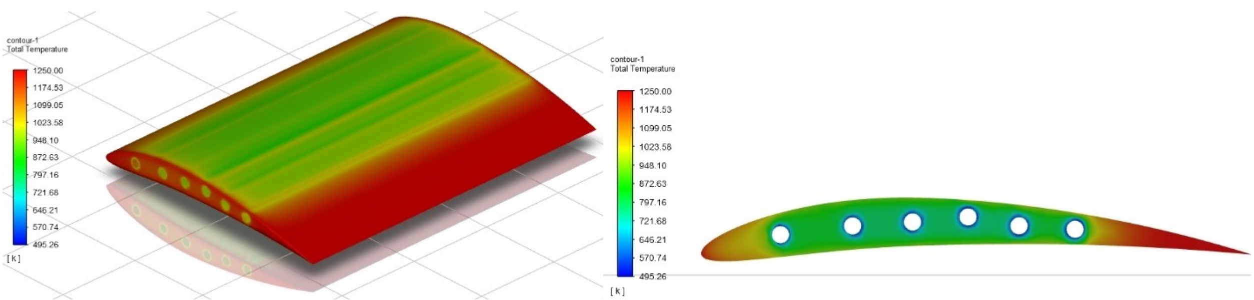
(a) (b)

Figure 16. Temperature Contour of 'Chromium Steel' (a) Isometric View (b) Cross-sectional View



(a) (b)

Figure 17. Temperature Contour of 'Haynes 188' (a) Isometric View (b) Cross-sectional View



(a) (b)

Figure 18. Temperature Contour of 'Inconel 718' (a) Isometric View (b) Cross-sectional View

In this analysis, three different high-temperature and corrosion-resistant alloy materials- Chromium Steel, Haynes 188, and Inconel 718 has been evaluated for their effectiveness in cooling turbine blades. The blade was initially hot, with a temperature of 1250 K. From the temperature contour, it is observed that the surface of the blade where the cool air has been passed through is comparatively cooler than the other part of the blade. The regions of highest temperature were represented in red, while the coolest areas were indicated in blue.

It is also revealed that Inconel 718 achieved the highest temperature reduction across both inline and staggered cooling hole configurations, with Chromium Steel being the least effective but still functional. The staggered hole configurations are more effective than inline configurations in reducing blade temperature due to their better air distribution arrangements. Furthermore, increasing the number of holes from 4 to 8 significantly improves cooling for all materials and enhances the performance of the turbine blade.

Heat Transfer Rate

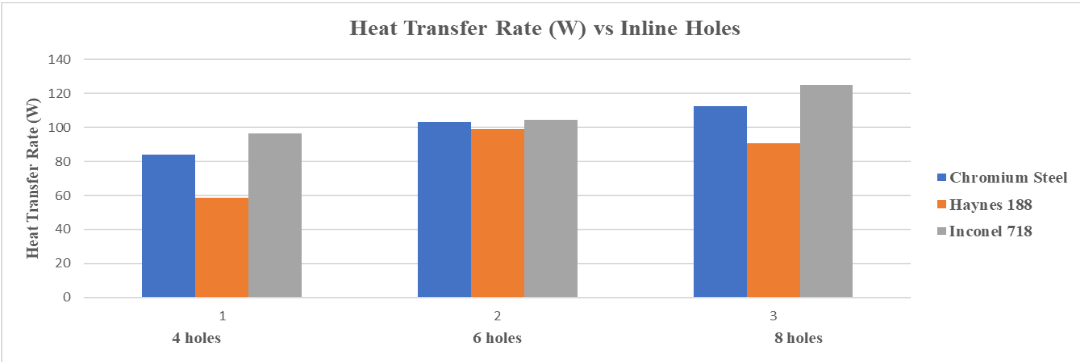


Figure 19. Heat Transfer Rate (W) vs Inline Holes with Different Materials

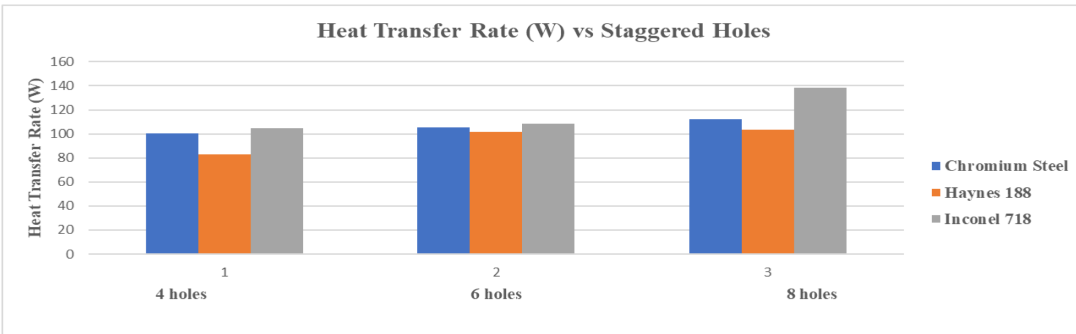


Figure 20. Heat Transfer Rate (W) vs Inline Holes with Different Materials

The results revealed that turbine blades constructed from Inconel 718 exhibited the highest heat transfer rates among the materials studied. This superior performance can be attributed to Inconel 718's higher thermal conductivity compared to Chromium Steel and Haynes 188. The enhanced thermal conductivity enables more efficient heat transfer from the blade surface to the coolant flow, thereby improving the blade's cooling efficiency.

The arrangement of cooling holes also significantly influenced the heat transfer performance. Staggered hole configurations demonstrated marginally better results than inline configurations. This improvement is due to the staggered arrangement's ability to promote more mixing of the coolant with the hot gas and led to improved heat removal. Additionally, the number of cooling holes also played a crucial role. An increased number of holes provided a larger cumulative cooling surface area, further enhancing the heat transfer rate.

CONCLUSION

Selecting the appropriate material for a turbine blade is important because it must exhibit exceptional temperature resistance to withstand the intense heat generated during operation without compromising structural integrity or performance. In this analysis, the influence of cooling circular hole configurations has been highlighted for three different materials, and staggered hole configurations promoted better coolant blade interaction and heat exchange due to the creation of a more disruptive flow path than the inline hole configurations. Additionally, increasing the number of holes from 4 to 8 resulted in lower blade temperatures by providing a larger overall cooling surface area. This study revealed that Inconel 718 with 9 staggered holes emerges as the most promising construction for turbine blades compared to the other models due to its exceptional heat transfer and temperature reduction capabilities.

Though the results are promising, experimental validation is crucial to confirm the accuracy and reliability of the simulation findings. To further enhance cooling performance, a strategically designed staggered hole arrangement with an optimized number of holes is recommended. Additionally, performing stress analysis can provide valuable information regarding the structural integrity of the blades. The suggested future work in this study includes altering the geometry, such as by tapering the blade slightly or creating elliptical holes. Moreover, modifying the cooling strategy to include techniques such as film cooling or jet impingement could lead to improved performance and operational efficiency of the blades.

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