NUMERICAL ANALYSIS OF TRAILING EDGE REGION COOLING IN HP STAGE TURBINE BLADE

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Abstract - Gas turbines are extensively used for aircraft propulsion, land-based power generation, and industrial applications. Thermal efficiency and power output of gas turbines increase with increasing turbine inlet temperature (TIT). The current TIT level in advanced gas turbines is far above the melting point of the blade material. Therefore, along with high temperature material development, a cooling scheme must be developed for continuous safe operation of high performance gas turbines. Cooling passages are incorporated into the trailing edge regions which are analysed to achieve maximum thermal performance in terms of cooling as well as structural integrity.

Keywords - Thermal analysis, Fins, Trailing edge cooling, Structural

I. INTRODUCTION

Gas turbines are highly effective engineered prime movers for converting energy from thermal form (combustion stage) to mechanical form – are widely used for propulsion and power generation systems. One method of increasing both the power output and thermal efficiency is to increase the temperature of the gas entering the turbine section. In the advanced gas turbines of today, the turbine inlet temperature can be as high as 1500°C; however, this temperature exceeds the melting temperature of the metal blades.

From Brayton cycle it is known that the increase in pressure ratio increases the gas turbine thermal efficiency accompanied with increase in turbine firing temperature. The increase in pressure ratio increases the overall efficiency at a
given temperature. However, increasing the pressure ratio beyond a certain value at any given firing temperature can actually result in lowering the overall cycle efficiency. As TIT increases, the heat transferred to the blades in the turbine also increases. The level and variation in the temperature within the blade material (which causes thermal stresses) must be limited to achieve reasonable durability goals.

II. LITERATURE REVIEW

Blade material with its thermal properties, thermal properties of air and the parameters used for comparison of various designs were obtained from papers by Kini et al [1][2][3]. Sin Chien Siw [4], Je-Chin Han et al [5], performed blade cooling analysis using a combination of ribs and pin fins. While analysis was performed on fins with the inlet and outlet in line with each other, in this project, fins were designed in the trailing edge to analyse the effect of airflow and thermal performance. Temperature dependent properties of blade material were obtained from specialmetals.com [6].

III. NUMERICAL MODEL

Ansys FLUENT is employed for analysis. The simulation uses the segregated solver, which employs an implicit pressure-correction scheme. The SIMPLE algorithm is used to couple pressure and velocity. Second order upwind scheme is selected for spatial discretization of the Reynolds Averaged Navier Stokes (RANS) equations as well as energy and turbulence equations.

Convergence is based on the residual which is $10^{-3}$ for continuity, thermal conductivity and epsilon while a minimum of $10^{-6}$ is set for energy.

A. Calculations

- **Characteristic Length**
  \[ L = \frac{2ab}{a+b} \]
  \[
  = \frac{2 \times 0.026 \times 0.012}{0.026 + 0.012} 
  = 0.0164 \, \text{m}
  \]

- **Velocity**
  \[ V = \frac{\dot{m}}{\rho A} = \frac{90/3600}{0.54 \times 0.000312} = 148.38 \, \text{m/s} \]

- **Reynolds Number**
  \[ R_e = \frac{\rho VL}{\mu} = \frac{0.54 \times 148.38 \times 0.0164}{3.186 \times 10^{-5}} \]
  \[ = 41246 \ (> 4000) \]

Based on the above calculations, it is concluded that the flow is turbulent and hence k-ε model is chosen.

B. Equations of Flow

Continuity:
\[
\frac{\partial}{\partial x_i} (\rho U_i) = 0
\]
(1)

Momentum:
\[
\frac{\partial}{\partial x_j} (\rho U_i U_j) = \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \bar{U}_i \bar{U}_j \right]
\]
(2)

Enthalpy:
\[
\frac{\partial}{\partial x_j} (\rho U_i T) = \frac{\partial}{\partial x_j} \left[ \mu \frac{\partial T}{\partial x_j} - \rho \bar{U}_i T \right]
\]
(3)
Energy:
\[
\frac{\partial}{\partial x_j} \left[ \rho u_j \left( h + \frac{1}{2} u_i^2 \right) \right] - \frac{\partial}{\partial x_j} \left( k \frac{\partial T}{\partial x_j} \right) = 0
\]  
(4)

Turbulence:
\[
\frac{\partial}{\partial x_j} (\rho U_j k) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) - \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon
\]  
(5)

Where, \( P_k = -\rho u_j u_j \frac{\partial U_j}{\partial x_j} \)  
(6)

\[
\frac{\partial}{\partial x_j} (\rho U_j \varepsilon) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_\varepsilon}) - \frac{\partial \varepsilon}{\partial x_j} \right] + c_{\varepsilon} \frac{\varepsilon}{k} P_k - \rho c_{\varepsilon} \frac{\varepsilon^2}{k} 
\]  
(7)

C. Boundary Conditions

A convective boundary condition of hot gas with free stream temperature of 1561 K [1]-[3] and convective heat transfer coefficient of 2028 W/m²K[1]-[3] is applied to the blade surface. A mass flow rate of 90 kg/hr[1]-[3] is given at the inlet with a temperature of 644 K [1]-[3].

The material of the blade is chosen as Nimonic Alloy 105 whose properties are shown below:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8010 kg/m³</td>
</tr>
<tr>
<td>Specific heat</td>
<td>419 J/kg °C</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>10.89 W/m °C</td>
</tr>
</tbody>
</table>

D. Grid Dependency

A line is chosen along the blade surface which is between 25%-30% of chord length. Figure 3 shows grid dependence test based on mesh size to check the quality of mesh for solution accuracy. It is clear from the figure that temperature values do not deviate more than 1% between mesh sizes of 2.5e-3m, 1e-3m, and 1.2e-4 m. Hence mesh size of 2.5e-3m is taken as the appropriate size due to reduced computational time. The mesh consists of 201883 nodes and 1094092 elements.

I. TRAILING EDGE REGION ANALYSIS

In the trailing edge, fins are introduced into the cooling passage to improve cooling. Three shapes are analysed to determine which would provide maximum and efficient cooling. A line is chosen along the blade surface which is between 25%-30% of chord length to compare each design based on temperature on the line.

A. Pin fin

Three rows of pin fins are arranged in two patterns. The first includes fins arranged in an
array, and in the second, fins are arranged in a staggered pattern. Analysis is performed to determine the most effective one which would be followed for the other shapes.

Based on the concept of increased surface area resulting in increased heat transfer, diameters of the fins are varied to determine the effect on thermal performance.

B. Triangular Fins

Triangular fins are modelled by maintaining the area constant. Additionally, the fins are arranged in four orientations to optimize airflow and provide the best thermal performance. Orientation is an important step of analysing since airflow can be studied which helps to analyse flow pattern, obstructions in flow, and the variation of turbulence. The orientations are shown below:

Airfoils are well known for their aerodynamics. Similar to the triangular fins, the airfoil fins too are arranged in the same four orientations. The orientations are shown below:
Fig. 4 Airfoil fins - (A) Orientation 1 (B) Orientation 2 (C) Orientation 3 (D) Orientation 4

Fins are created in the trailing edge to increase heat transfer, thus improving cooling. Three shapes and four orientations are tested and analysed. Comparison is done by temperature and airflow around the fins and within the blade.

V RESULTS AND DISCUSSIONS

A. Pin fin

TABLE II COMPARISON BETWEEN ARRAY AND STAGGERED ARRANGEMENT OF FINS

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Arrangement</th>
<th>Line Temperature (K)</th>
<th>Area weighted average (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>Array</td>
<td>1044.08</td>
<td>1321.02</td>
</tr>
<tr>
<td>2</td>
<td>Staggered</td>
<td>1029.86</td>
<td>1320.82</td>
</tr>
</tbody>
</table>

From Table I, it is seen that staggered arrangement of fins is better than that of array. This can be clearly justified by Figure 3 which shows the line temperature plot and Figure 4 which shows the path lines of air in the cooling channel. In an array arrangement of fins, when the incoming air comes in the contact with the first few rows of fins, velocity reduces and is not able to cool the fins which are further ahead. This causes higher temperatures at the top of the blade resulting in majority of the blade being hotter. However, in a staggered arrangement, fins are placed in a triangular manner which causes air to come in contact with the first few rows and divert outward (towards the adjacent columns of fins). This results in a cooler blade.

1) Diameter analysis:
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TABLE III DIAMETER ANALYSIS OF PIN FINS

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Diameter (mm)</th>
<th>Line Temperature (K)</th>
<th>Area weighted average (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1010.46</td>
<td>1406.07</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1000.75</td>
<td>1347.46</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>1029.86</td>
<td>1320.82</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>1054.83</td>
<td>1327.9</td>
</tr>
</tbody>
</table>

Fig. 5 Line temperature plot of varying diameters

B. Triangular Fins

TABLE IV COMPARISON BETWEEN ORIENTATIONS OF TRIANGULAR FINS

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Orientation</th>
<th>Line Temperature (K)</th>
<th>Area weighted average (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1071.3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1064</td>
<td>1240.7</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1068.0</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1046.0</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 6 Line temperature plot of different orientations of triangular fins

From the table, it is seen that judging the most effective orientation is very difficult if only line temperature is used as a parameter, hence, along with line temperature, area weighted average plays a crucial role in determining the optimum orientation. While the aim is to reduce the highest temperature on the blade, it’s also important to cool the entire blade surface. Keeping this in mind, the two parameters for each orientation is compared and orientation 3 comes out to be the most effective one.

C. Airfoil Fins
Similar to triangular fins, it’s difficult to judge the optimum orientation by line temperatures, hence, line temperatures and area weighted average give a clear idea about the optimum orientation. While orientation 3 was the best for triangular fins, it’s not necessary that the same orientation would have the same effect on different shapes. This is because every shape diverts and directs flow in different patterns, thus making it important to analyze all orientations for every shape. For airfoil fins, orientation 4 provides the least temperatures across the blade, hence orientation 4 the optimum one.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Orientation</th>
<th>Line Temperature (K)</th>
<th>Area weighted average (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1060.3 9</td>
<td>1300</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1051.5 6</td>
<td>1245.7 5</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1040.3 6</td>
<td>1262.7</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1045.0 5</td>
<td>1255.7 8</td>
</tr>
</tbody>
</table>

D. Structural

In addition to creating cooling passages for the blade, it’s necessary to analyze the structural integrity of the blade. After obtaining the model which provides the best thermal performance, a structural analysis performed and a deformation of 1.8mm was found. This shows that the design was within maximum limits and in fact better. Hence, the model provides effective cooling as well as maintains structural integrity of the blade.

VI. CONCLUSIONS

In this study, numerical methodologies for conjugate heat transfer and life estimation are developed and analyzed. The results of heat...
transfer show improved cooling. The methods are developed to improve the fidelity of durability analysis for internally cooled blade.

- It is seen that the use of fins in the trailing edge and by analysing different shapes and their orientations respectively, thermal performance can be improved
- From structural analysis, it is seen that the maximum deformation and is within permissible limits

**NOMENCLATURE**

TIT − Turbine inlet temperature in K  
\( \dot{m} \) − Mass flow rate of coolant air in kg/hr  
\( \rho \) − Density of coolant air in kg/m\(^3\)  
A − Area of inlet duct in mm\(^2\)  
\( \mu \) − Dynamic Viscosity of coolant air  
\( R_e \) − Reynolds Number

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