Computational Study of the Thermal Performance of an Unshrouded High Pressure Turbine Blade Tip

Chao Zhou, Howard Hodson
Whittle Laboratory,
Department of Engineering,
University of Cambridge,
United Kingdom
cz239@cam.ac.uk

Abstract: The tip leakage flow imposes large thermal loads on unshrouded high pressure turbine blades. Obtaining a good thermal performance of the blade tip represents a major challenge for the turbine designer. In this paper, numerical methods have been employed to study the thermal performance of a flat tip and a cavity tip at five tip gaps of 0.4%, 1%, 1.6% 2.2% and 2.8% of the chord. For the flat tip, the tip leakage flow separates from the sharp pressure side edge then reattaches on the blade tip. The reattachment region suffers from a high heat transfer coefficient. As the size of the tip gap increases, the average heat transfer coefficient on the flat tip first increases then decreases. For a cavity tip, areas of high local heat transfer coefficient on the tip were observed on the tip surfaces where the tip leakage flow reattaches. At tip gaps smaller than 1.6% chord, the average heat transfer coefficient on the cavity tip decreases significantly if the tip gap decreases. The cavity tip has a lower average heat transfer coefficient than the flat tip at tip gaps smaller than 2.5% chord. However, because the surface area of the cavity tip is 1.38 times that of the flat tip, the cavity tip has a higher thermal load than the flat tip at all of the tip gaps studied.

Key-Words: Turbine, Tip, Leakage flow, Heat transfer, Thermal, CFD, Thermal load, Spalart-Allmaras

1 Introduction

In unshrouded high pressure turbines, the tip leakage flow causes high metal temperatures on the tips of the first row of the rotor blades. Heyes et al. [1] studied the leakage flow pattern over the tip. The leakage flow pattern determines the thermal performance of the tips. Ameri et al. [2] noted that CFD tools can give a good representation of the tip thermal performance, but also noticed a problem due to the difficulty in predicting the separation of the tip leakage flow from the pressure side corner of the tip. Krishnababu et al. [3] found close agreement of the predictions with their experimental data, and the CFD results provided insight into the nature of the tip leakage flow. However, discrepancies were also found due to problems associated with the prediction of the separation zones. Newton et al. [4] and Bunker et al. [5] studied the thermal performance of different blade tips on different blade profiles using experimental methods. Regions of high heat transfer coefficients appear on the blade tips due to the flow reattachment and impingement.

This paper describes a study of the thermal performance of unshrouded turbine blade tips. The objectives are to study the heat transfer on a flat tip and a cavity tip and to compare the thermal performance of these two tips.

2 Numerical Method

2.1 Computational Domain and Mesh

This paper follows the experimental work that has been conducted on a cascade in the Whittle Laboratory [4]. The computational domain is based on the experiment and is shown in Fig. 1. Some parameters of the cascade are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord</td>
<td>223mm</td>
</tr>
<tr>
<td>Axial Chord</td>
<td>103mm</td>
</tr>
<tr>
<td>Pitch/Chord ratio</td>
<td>0.83</td>
</tr>
<tr>
<td>Span used in the CFD</td>
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</tr>
<tr>
<td>Inlet flow angle</td>
<td>32.5</td>
</tr>
<tr>
<td>Exit flow angle</td>
<td>75.6</td>
</tr>
<tr>
<td>Zweifel Coefficient</td>
<td>0.73</td>
</tr>
<tr>
<td>$Re_2 = \rho v 2C/\mu$</td>
<td>$2.2 \times 10^5$</td>
</tr>
</tbody>
</table>

Table 1 Parameters of the Cascade
The numerical simulations were produced by the commercial code FLUENT 6.3 solving the steady RANS equations. The segregated solver with SIMPLC pressure-velocity coupling was selected. The second order upwind scheme was used for discretization.

The different versions of the Spalart-Allmaras turbulence model, k-ω turbulence model and k-ε turbulence model in Fluent 6.1, Fluent 6.2 and Fluent 6.3 were examined for the case of the flat tip. Among all of these turbulence models, the Spalart-Allmaras model of Fluent 6.3 produces the best prediction of the distribution of the heat transfer coefficient on the flat tip. Therefore, the Spalart-Allmaras turbulent model was used to study this problem.

Periodic boundary conditions were applied to a single blade to simulate a row of blades. Based on the measured data, a turbulent inlet boundary layer, with a 99 percent thickness of 2.24% C and a shape factor of 1.3, was applied at the inlet. The specified turbulence intensity at the inlet was 1%. The measured free stream total pressure of 162 Pa-gauge was applied at the inlet of the cascade. Atmospheric pressure (0 Pa-gauge) was applied at the exit of the computational domain. The cascade exit Reynolds number was \( 2.2 \times 10^3 \) based on the blade chord and the cascade exit condition.

No slip boundary conditions were applied to all walls. Since the tip leakage flow only affects the near tip region of the flow, a span of 120 mm from the tip was considered. A symmetry boundary condition was used for the ‘hub’ of the computational domain.

The CFD simulations were run with a constant inlet gas total temperature of \( T_1 = 315 \text{ K} \) and a constant wall temperature of \( T_w = 290 \text{ K} \) to obtain the heat transfer coefficient \( h \) on the blade surface. The heat transfer coefficient is defined as:

\[
h = \frac{q}{(T_1 - T_w)},
\]

where \( q \) is the local heat flux per unit area.

Fig. 3 Grid Dependency Study of Flat Tip (\( \tau = 1.6\% \text{ C} \))

Fig. 3 shows the results of the grid dependency study for the S-A turbulence model. The variation of the heat transfer coefficient is less than 10% for \( Y^+ \) from about 0.5 to nearly 6. The mesh with an average tip \( Y^+ \) of about 0.7 on the tip is used for the numerical study. The maximum \( Y^+ \) on all of the walls is less than 3.

3 Results and Analysis

3.1 Flat Tip

Figure 4 shows the flow over a flat tip. A separation zone can be seen along the tip pressure side edge underneath the tip leakage flow. The path lines in the separation bubble start near the blade leading edge. The colour indicates that the velocity magnitude is relatively low in the separation zone. Over the separation zone, the tip leakage flow accelerates from the pressure side edge to the vena-contracta, and then decelerates and mixes as it travels through the tip gap. After exiting the tip gap, it...
mixes with the main flow in the blade passage, forming the tip leakage vortex. On the contour map of the velocity distribution at the cut plane, the low velocity region on top of the tip near the pressure side edge indicates the presence of the separation zone. This region extends a distance of \( 3\tau \) into the tip gap at the cut plane, where the tip leakage flow reattaches on the tip. The vena-contracta, where the stream tube containing the tip leakage flow contracts to its minimum height, appears at a distance of about \( 1.3\tau \) into the gap, where the separation bubble reaches its biggest height and results in a contraction coefficient \( \sigma \) of 0.68. The measurements of Heyes [1] show that the highest velocity outside the separation bubble happens at \( 1.5\tau \) into the gap with a \( \sigma \) of 0.66. The contraction coefficient given in this paper is obtained by visually examining the velocity distribution of the cut plane. The \( \sigma \) is under predicted and this suggests that the height of the separation bubble is under predicted. This will have an effect on the distribution of the heat transfer coefficient on the tip.

![Fig. 4 Predicted Flow around a Flat Tip (\( \tau = 1.6\% \text{C} \))](image)

| Table 2 Comparison of Predicted Results |
|-----------------|------------------|
| Experiment      | 0.66             |
| CFD             | 0.73             |
| average \( h \) (W/m\(^2\)K) | 110              |
| 93              |

The low heat transfer coefficient region between this high heat transfer coefficient region and the pressure side edge is the area underneath the separation zone. Another high heat transfer coefficient region can be seen on the suction side near leading edge part marked ‘A’. This is also due to the flow separation and reattachment.

Although the average and the peak value of the heat transfer coefficients are under predicted, the CFD produces a good prediction of the heat transfer coefficient distribution.

![Fig. 6 Contour Maps of Heat Transfer Coefficient on the Flat Tip, CFD](image)

![Fig. 5 Contour Maps of Heat Transfer Coefficient on the Flat Tip (\( \tau = 1.6\% \text{C} \))](image)
separation zone starting from the pressure side becomes narrower and the reattachment, which results in high heat transfer coefficient region, becomes closer to the pressure side edge.

For a large tip gap of 2.8%C, as shown in Fig. 6(b), the size of the separation zone over the tip is larger and the reattachment occurs further from the pressure side edge. So the region of low heat transfer coefficient along the pressure side edge is wider.

3.2 Cavity Tip

Cavity tips are widely used in high pressure turbines. The height and the thickness of the squealers for the cavity tip of current study is 2.24%C.

Figure 7(c) shows the flow around the cavity tip. The tip leakage flow separates over the pressure side squealer, and a separation zone can be seen over the pressure side rim. The tip leakage flow goes into the tip cavity, mixes with the flow inside and rolls up. The vortex in the cavity propagates towards the trailing edge along the suction side squealer after about 1/3 of the chord. As shown in the velocity contour map, the width of the vena-contracata over the pressure side squealer is similar to that of the flat tip. The estimated contraction coefficient $\sigma$ is 0.70. Another vena-contracata exists over the suction side squealer, and has a contraction coefficient $\sigma$ of 0.95. A previous study has shown that the cavity tip has less tip leakage loss than the flat tip [1]. In fact, the lower velocity magnitudes at the vena-contracatae indicate that there is a lower tip leakage mass flow rate than in the case of the flat tip.

Fig. 8 show the contour maps of heat transfer coefficient on the floor and the squealer top surface of the cavity tip at tip gap of 1.6%C. On the cavity floor near the leading edge, a high heat transfer coefficient zone marked ‘B’ is presented due to the flow impingement after the flow separation from the tip. Apart from this region, the heat transfer coefficient on the cavity floor is low, because of the low velocity magnitude in the cavity. On the pressure side of the squealer rims, the heat transfer coefficient is low near the pressure side edge underneath the separation zone. The flow reattaches in the area marked ‘C’ in Fig.8 (b). This results in a high heat transfer coefficient region. On the top surface of the suction side squealer, high heat transfer coefficients appear on the areas where the flow reattaches.

Fig. 9 presents the heat transfer coefficient on the inner surfaces of the squealers as well as on the pressure and suction side of the blade. Areas of high heat transfer coefficient appear near the leading edge on inner surfaces of both the pressure side and the suction side squealers due to vortex impingement. From the middle chord towards the trailing edge, the flow in the cavity is dominated by the slow recirculation, so the heat transfer coefficient is low. However, high heat transfer coefficients appear near the top of the suction side inner squealer surface,
which is marked ‘E’ in Figure 9(b). When compared with the flat tip, the cavity tip has 38% more area due to the area of its inner surface. The heat flux goes into these squealers increases the thermal load on the cavity tip.

In Fig. 9(a), high heat transfer coefficients can be found on the suction side of the blade surface near the blade tip in the area marked ‘D’. This is because the tip leakage flow exits the tip gap and impinges on the blade suction side surface. High heat transfer coefficients also appear on the pressure side very near the tip, as shown in Figure 9(b). This is because the flow accelerates into the tip gap.

In Fig. 9(a), high heat transfer coefficients can be found on the suction side of the blade surface near the blade tip in the area marked ‘D’. This is because the tip leakage flow exits the tip gap and impinges on the blade suction side surface. High heat transfer coefficients also appear on the pressure side very near the tip, as shown in Figure 9(b). This is because the flow accelerates into the tip gap.

![Fig. 10 Contour Maps of Heat Transfer Coefficient on Cavity Tips, CFD](image)

Fig. 10(a) shows the distribution of the heat transfer coefficient on the cavity tip at a small tip gap of 0.4%C. The tip leakage flow reattaches to the pressure side rim, which results in high local heat transfer coefficient. However, the heat transfer coefficient on the suction side rim is low. At a large gap of 2.8%C as shown in Fig. 10(b), the separation that starts from the pressure side edge is much larger and the reattachment occurs on the suction side rim. As a result, the heat transfer coefficient on the pressure side rim decreases and the heat transfer coefficient on the suction side rim increase.

In Fig. 10, the heat transfer coefficient on the cavity floor increases significantly as the tip gap increases from 0.4%C to 2.8%C. As shown in Fig. 11, when the size of the tip gap increases, the flow velocity in the cavity increases. As a result, the heat transfer coefficient increases. When increasing the tip gap from 1.6%C to 2.8%C, Fig. 8(b) and Fig. 10(b), the heat transfer coefficient on the floor of the cavity tip only changed slightly. This is because the velocity of the flow in the cavity does not change much. The same trend is found on the inner surface of the squealers, because the flow in the cavity affects the heat transfer both on the cavity tip floor and on the inner surfaces of the squealer.

![Fig. 11 Velocity Contour Maps of Cavity Tip, CFD](image)

**3.3 Comparison of Flat Tip and Cavity Tip**

Figure 12 shows the average heat transfer coefficient on the flat tip and the cavity tip.

![Fig. 12 Overall Average Heat Transfer Coefficient on Blade Tips (CFD)](image)

The cavity tip has a lower average heat transfer coefficient at tip gaps smaller than 2.5%C. Newton et al. [4] experimentally investigated the thermal performance of the flat tip and the cavity tip at tip gaps from 1.6%C to 2.8%C. The experimental results show that in this range of the tip gap, the cavity tip has an average heat transfer coefficient that is similar to that of a flat tip, and the average heat transfer coefficient does not change much over this range of tip gaps.

The thermal load on a tip is the heat flux that goes into the tip. The heat flux into the blade tip is:

\[
Q = \int_A h \cdot (T_i - T_w) \cdot dA
\]

where \(A\) is the area of the blade tip surfaces.

![Fig. 13 Thermal Loads of Different Tips](image)
As shown in Fig. 13, the prediction shows that the cavity tip suffers from a higher heat flux than the flat tip at all five tip gaps. This is because the surface area of the cavity tip is 1.38 times of the flat tip due to the inner squealer surfaces. Therefore, although the cavity tip has a lower average heat transfer coefficient at small tip gaps, the total heat flux that enters the cavity tip is higher.

4 Conclusions

The thermal performance of a flat tip and a cavity tip is studied with numerical methods.

For the flat tip, the tip leakage flow separates from the sharp pressure side edge then reattaches on the blade tip. The reattachment region suffers from a high heat transfer coefficient. As the size of the tip gap increases, the average heat transfer coefficient on the flat tip first increases then decreases.

For a cavity tip, areas of high local heat transfer coefficient on the tip were observed on the tip surfaces where the tip leakage flow reattaches. At tip gaps smaller than 1.6%C, the average heat transfer coefficient on the cavity tip decreases significantly as the tip gap decreases.

The average heat transfer coefficient of the cavity tip is lower than that of the flat tip at tip gaps less than 2.5%C. However, because the surface area of the cavity tip is 1.38 times that of the flat tip, the total heat flux that enters the cavity tip is higher.

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