Numerical Study of the Leakage Flow on a Novel Turbine Blade Tip

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Abstract

The traditional squealer tip of turbine blade performs good property in decreasing the leakage mass flow rate. The improvement of the aerodynamic performance for turbine blade tip is always continuing associated with the understanding of the leakage flow characteristic. Thus, a novel turbine blade tip, which is derived from the conventional squealer tip, is investigated numerically in this paper. The characteristic of the tip region flow field, the tip blade loading distribution and the tip leakage mass flow is analyzed in detail.

The results show that, first some part of the tip region flows are forced to flow downstream along the guided groove formed by the recessed pressure side rim, which contributes to the preventing of the leakage mass flow and the descending of leakage loss as well. Besides, the blade loading of the novel geometry is raised than the traditional squealer tip, which reveals that the mass flow rate of the working fluid is increased. Third, the leakage mass flow is reduced so that the efficiency is increased. The CFD analysis predicts that, the novel squealer tip case shows 30% less leakage mass flow and a 0.11% total isentropic efficiency increase for a single rotor compared to the baseline squealer tip case.

Keywords: Tip leakage flow; Squealer tip; Recessed pressure side rim; Aerodynamic performance

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1. Introduction

The tip leakage flow has been investigated analytically, experimentally and numerically for decades[1~9]. Tip leakage flows of unshrouded axial turbine are an important loss source, because of the inevitable tip clearance of turbine rotors, which allows fluid to cross over the blade tip from the pressure side to the suction side as a result of the transverse driving pressure difference between the two sides of the blade. The tip leakage losses could contribute to roughly as much as 30% of the total losses in a turbine stage. The leakage flows go through the blade tip under the effect of the circumferential driving pressure difference between the blade pressure side and the blade suction side. Actually, the leakage area and the driving pressure is the direct reason of tip leakage flows.

Tip leakage flows have two significant effects on the passage flow. Firstly, the mass flow of the working fluid turned by the blades is reduced due to the tip leakage flows crossing the gap, which leads to the decreasing of the work output. Secondly, tip leakage flows interact with the passage secondary flows because of the differences of the velocity magnitude and direction between them, which results in much additional mixing loss.

The design of the blade tip geometry is an effective method to improve the aerodynamic performance of a turbine. Cengiz C.[10] investigated the aerodynamic characteristics of full and partial-length squealer rims in a single cold turbine research experimentally. The results indicate that the use of partial squealer rims can positively affect the local aerodynamic field by weakening the tip leakage vortex, and the suction side partial squealers are aerodynamically superior to the pressure side squealers and the channel arrangement.

Prakash C.[11] studied the aerodynamic performance of a vertical shelf and a inclined shelf configuration by comparing with a conventional squealer tip numerically. It was found that, on the pressure side tip corner, the inclined shelf induces a separation bubble (vena-contracta effect) which decreases the height of the leakage clearance, resulting in a dominant factor to reduce the leakage mass flow rate and improve efficiency. The inclined shelf also shows a reduced efficiency derivative with clearance.

Bob M.[12] presented an improved design of a recessed blade tip for a highly loaded axial turbine rotor blade. It was observed that, the total tip heat transfer Nusselt Number was significantly reduced, being 13% lower than the flat tip and 7% lower than the baseline recess shape. Experimental measurement showed an overall improvement of 0.2% in the turbine total efficiency compared to the flat tip case. The CFD analysis predicted a 0.38% total efficiency increase for a single rotor equipped with the new recess design compared to the flat tip rotor.

L. Willer[13], Z. Schabowski[14], Chao Zhou[15] had investigated the aerodynamic performance of various combinations of squealer and winglet geometries numerically and experimentally. It was also found a reduction of tip leakage mass flow rate and loss, an improvement of the aerodynamic performance. Their results agreed well with the work of each other.

The blade tip shape, which is related to the separation bubble scale, plays a considerable role to the blade tip flow pattern and the leakage mass flow rate. A novel turbine blade squealer tip geometry with a recessed pressure side rim was investigated by compared with a flat and a traditional squealer tip (as shown in Fig.1) in this study. This novel squealer tip not only utilized the vena-contracta effect, but also involved the mechanism of the flow guided design.

| Nomenclature          |
|-----------------------|
| $m$                   | mass flow rate         |
| $Ma$                  | Mach number            |
| $\xi$                 | total pressure loss coefficient |
| $\eta$                | efficiency of turbine stage |
| $m_{LPS}$             | leakage mass flow rate of the pressure side |
| $p_{t,\text{in}}$     | total pressure of the inlet |
| $p_t$                 | total pressure         |
| $p_{s,\text{out}}$    | static pressure of the outlet |
2. Numerical Simulation

The numerical investigation of the tip leakage flow of this paper was conducted in a two stage high pressure turbine, in order to evaluate the benefits for a single stage in a high pressure turbine. Meanwhile, it could avoid the inaccuracy of the exerting boundary condition on a single rotor as much as possible. Therefore, the overall computational domain was set up as four rows (as shown in fig.2), of which the interface between the stator and the rotor was chose as stage.

The novel blade tip was applied only in the rotor of the first stage, which was created by UG. The height of the clearance is 0.4mm, the depth of the squealer tip is 1.5mm, and the width of the squealer tip is 1mm. For the novel case, the length of the recessed pressure side rim is the same as the cavity, the height is 3mm, and the quasi-lean-angle of the pressure squealer is $45^\circ$. Full structure mesh was also generated by commercial software ICEM CFD. The near wall areas were refined, and the $Y+$ values on the blade tip walls were in between 0 and 5, $Y+$ values on the blade surface were below 10.

![FLAT TIP](image1)
![SQUEALER TIP](image2)
![NOVEL SQUEALER TIP](image3)

Fig.1. Three Different Blade Tip Geometries

The flow field of the proposed turbine cases was solved by a three-dimensional, steady, viscous CFD code, Ansys CFX 13.0, which is controlled by the Reynolds-Averaged Navier-Stokes (RANS) equation. The SST turbulence model associated with automatic wall function was employed. The inlet boundary conditions were given by uniform total pressure, total temperature, flow angles, turbulent intensity and length scale. The outlet condition was given by constant static pressure. This numerical simulation method was used and validated by Tang H.\cite{16}.

![Fig.2.The Overall Computational Domain](image4)
![Fig 3 3D Computational Mesh Detail of the Novel Squealer Tip](image5)
3. Results and Discussion

3.1. Tip Region Flow Field

The secondary flows of the tip region are dominated by the tip high-speed leakage jet. Fig.4 gives the streamlines in the tip region of the three different tip geometries. The seed points are released from the imaginary clearance leakage surface in fig.4 (a), and from the pressure side tip region in fig.4(b).

The tip leakage flow from the blade tip pressure to the suction side is generated under the influence of the transverse driving pressure difference. Specifically, from the pressure side view, some tip flows cross the flat tip gap from the pressure to the suction side in front of the tip clearance. Then they are rolled up into the passage vortex. However, these leakage flows cross over the pressure side squealer, and flow into the cavity formed by the squealer tip. Finally, they are delayed to leak by 30% true chord in the other two cases as shown in fig.4 (a). Some other tip flows inflow the gap from the head of the suction side, and outflow at about 30% true chord position to join the passage vortex.

Subsequently, along with the increasing of the transverse difference pressure, the tip leakage vortex is generated on the blade suction side due to the interaction between the leakage jet and the boundary layer of the suction tip corner. And another part of leakage flow gets around the tip leakage vortex to feed into the passage vortex, because it interacts with the up-endwall boundary layer which is also scraped by the rotation of the blade.

![Fig.4. Streamlines in the tip region](image-url)
Since the sustained leakage mass feeding, the scale is increased and the strength is intensified for the tip leakage vortex and passage vortex with the development of the leakage flow field. From the suction side view, the most significant characteristic of the three cases is that, a large part of the tip leakage flows are hold back by the recessed pressure side rim which forming a guided groove in the novel case. These flows have passed through the flat tip directly. But, they generate a vortex within the pressure side corner of the inner cavity and have been delayed to leak starting from about 30% true chord position. Fig.5 is the detail schematic of the flow in the guided groove. It could be seen that these flows are prevented to flow to the trailing edge along the recessed pressure side rim. It is a new leakage control mechanism besides the separation bubble.

Fig.5. Detail Schematic of the Flow in the Guided Groove

Fig.6 shows the tip leakage flow vector over the pressure side of the rim of the three cases. The flow vectors around the pressure side squealer tip are quite difference as a result of the sharp corner in the novel case. The sharper corner induces a larger turning angle of the inflow tip leakage flow. Furthermore, Fig.7 presents the Mach contour of the pressure side corner of the three cases with the legend scale between 0.3 and 1.3. The tip mass flow is chocked significantly within the flat tip clearance due to the contraction of the tip leakage gap. Obviously, the sharper tip corner on the pressure side of the novel case induces a larger separation bubble which reduces the leakage area compared with the traditional squealer tip.
Fig. 6. Tip Leakage Flow Vector over the Pressure Side of the Tip

Fig. 7. Mach Contour of the Pressure Side Corner in the 83% Axial Chord Section

3.2. Blade Loading Distribution

Fig. 8 is the relative static pressure distribution of the three different tip geometries blade surface in 99% span. It could be seen that the blade loading of the squealer tip is fuller than the flat tip on the pressure side, and the blade loading is further raised by the recessed pressure side rim. It reflects that the work output of the novel tip geometry has been increased obviously.
Fig. 8 presents the relative static pressure distribution of the mid gap polyline in the three case. The static pressure distribution of the pressure side rim of the flat case is the lowest of the three because of the flow acceleration in the almost constant contraction clearance. However, in the other two cases, it is higher than the flat case owing to the low pressure signal of the suction side could not affect the pressure side, because that the tip cavity forms a recirculation zone with complex vortex structure\(^{[12]}\) as shown in fig. 4 (a). As a result, the incoming leakage flows over the pressure side squealer cannot reach the suction side squealer in the upstream region of the cavity. But they still have to leak over the suction side squealer with the increasing of the transverse driving difference pressure, the decreasing of the cavity width and the ending of the cavity.

Fig. 10 shows the relative static pressure distribution of two side squealer tip surface of the novel case in 99% span. Fig. 11 gives the Mach contour of the three cases in 99.5% span. Actually, the tip blade loading is splitted into two parts by the two tip squealers similar as a winglet\(^{[14]}\). The transverse pressure difference of the pressure side squealer tip is small in correspond with a subsonic flow. But the transverse pressure difference of the suction side squealer tip is large enough to make the leakage jet reach a supersonic state. In addition, the max value of the Mach number is reduced by the recessed pressure side rim.
3.3. Tip Leakage Mass Flow

Bob M. [12] evaluated the tip leakage mass flow rate for the aerodynamic performance since it is intensively related to the total pressure loss. Simply, the tip leakage mass flows are the feed source of the tip leakage vortex and the tip passage vortex. A steady feed source flow could keep the scale and the intensity of the two vortices. Obviously, the increase of the tip leakage mass flow rate would lead to larger and stronger vortices which raise the total pressure loss.

Fig.12 has given the mass flow distribution of the three different rotor blade tip geometries along the imaginary leakage surface of the tip clearance. This picture could be divided into two parts from the blade leading line as shown below. The left part of the lines is relative to the suction side of the imaginary leakage surface, with positive value representing outflow of the tip leakage flow. The lines on the right hand are relative to the pressure side of the imaginary leakage surface; similarly, the negative value means the inflow of the leakage flow.

It could be seen from the suction side imaginary leakage surface that, for the flat tip case, there are tip flows outflow between 0~10% axial chord position, inflow between 10~30%, and outflow between 30~100%. The tip leakage mass flow rate is intensified and weakened along with the variation of the transverse pressure difference combined with fig.8. For the other two cases, the tip leakage mass flow rate is reduced by the tip cavity formed by the squealer tip between 40~65% axial chord position. But it is increased starting from the rear of the inner cavity, where the leakage flows have to outflow, to the trailing edge.

Table 1 gives the performance parameter of the first stage. The integral surface of the leakage mass flow rate is the pressure side imaginary leakage surface as shown at the top-right corner of Fig.12. The squealer tip case performed a reduction of 21% in the leakage mass flow when compared to the flat tip, the novel squealer tip case showed 30% less leakage mass flow compared to the baseline squealer tip case. As a result, it reveals a declining of the total pressure loss coefficient and a increasing of the efficiency. The CFD analysis predicts a 0.11% relative total isentropic efficiency increase for a single rotor with the novel squealer tip compared to the baseline squealer tip case.
Fig. 12. Mass flow rate distribution along the imaginary leakage surface

Table 1. Performance Parameter of the First Stage

|                  | $m_{LPS}$ | $\xi$   | $\eta$     |
|------------------|-----------|---------|------------|
| FLAT TIP         | 1.00      | 1.00    | 100.00%    |
| SQUEALER TIP     | 0.79      | 0.99    | 100.12%    |
| NOVEL SQUEALER TIP | 0.49      | 0.97    | 100.23%    |

Fig. 13 gives the tip region total pressure loss coefficient distribution contour of the outlet plane. The total pressure loss coefficient is defined as below:
Where, \( \bar{p}_{t, \text{in}} \) is the mass flow average total pressure of the inlet, \( \bar{p}_t \) is the local mass flow average total pressure, \( \bar{p}_{\text{s, out}} \) is the mass flow average static pressure of the outlet.

As is vividly indicated in this contour, in the tip region of the outlet plane, the total pressure loss coefficient of the squealer tip case is decreased by the squealer tip compared with the flat tip case. And it is further reduced by the recessed pressure side rim.

4. Conclusion

A numerical investigation of an improved squealer tip with a recessed pressure side rim has been presented in this paper. The tip region flow field, the tip loading distribution, the tip leakage mass flow rate and the total pressure loss distribution is analyzed, in order to demonstrate the improvement of the aerodynamic performance by the guided groove. The conclusions can be drawn as below:

- Some part of the tip region flows are forced to flow along the guided groove formed by the recessed pressure side rim downstream to the trailing edge, which contributes to the preventing of the leakage mass flow and the descending of mixing loss as well.
- The sharper squealer tip corner on the pressure side of the novel squealer tip forces the leakage fluid flows to turn by a larger angle, which induces a larger separation bubble (vena-contracta effect) than the traditional squealer tip.
- The blade loading of the novel squealer tip is raised comparing with the traditional squealer tip, which reveals that the mass flow rate of the working fluid is increased.
- The leakage mass flow is reduced so that the efficiency is increased. The CFD analysis predicts that, the novel squealer tip case shows 30% less leakage mass flow and a 0.11% total isentropic efficiency increase for a single rotor compared to the baseline squealer tip case.

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