Influences of Squealer Tip Geometrical Characteristics on Tip-leakage Flow in Turbine Rotor

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ABSTRACT
Tip-leakage loss caused by tip-leakage flow is an important source of aerodynamic loss in turbine rotor. Squealer tips are often used to control the tip-leakage flow and loss. In this paper, a transonic single-stage high-pressure turbine is simulated numerically to investigate the effects of cavity width and height on tip-leakage flow and loss. Based on plenty of cases with various cavity widths and heights, it is found that the optimal value of cavity height is 2.5-3.0 times clearance height and the optimal value of cavity width is affected by cavity height. The decrease of cavity width and the increase of cavity height of cavity have similar effects on the evolution of the scraping vortex. The cavity width controls the tip-leakage loss by suppressing the breakdown of the tip leakage vortex and reducing the corresponding mixing loss. However, the cavity height mainly affects the loss inside the clearance.

INTRODUCTION
Due to the tip clearance and pressure difference between the two sides of rotor blade, tip-leakage flow is inevitable in the unshrouded turbine rotor. Tip-leakage flow has a significant adverse effect on the aerothermal performance of the turbine. The loss caused by tip-leakage flow can account for more than 30% of the total aerodynamic loss of rotor passage (Denton, 1993). Therefore, effective control of tip-leakage flow is of great significance to improve turbine aerodynamic performance.

Squealer tip is an effective and feasible passive control method for tip-leakage flow, which is often used in unshrouded high pressure turbines (Bunker, 2006). There are complex vortex structures in the tip region of rotor with squealer tip. Besides the tip leakage vortex (TLV) in the channel, there are scraping vortex (SV), pressure side squealer corner vortex (PSCV) and suction side squealer corner vortex (SSCV) inside the cavity (Mischo et al., 2008). The series of vortices inside the cavity, especially the SV, have a blocking effect on the tip-leakage flow (Zhou, 2015). The SV is significantly affected by the relative motion of the casing (Virdi et al., 2015). In the further studies of the controlling mechanism, Zou et al. (2017) found that the SV inside the cavity acts as a labyrinth tooth, thus forming the aero-labyrinth liked sealing effect. The study has made it clear that the SV plays a dominant role in the controlling of the tip-leakage flow. So far, the control mechanism of squealer tip on the tip-leakage flow has been fully studied and understood, which provides a guide for the geometric optimization of squealer tips.

The geometric optimization of squealer tips involves many geometric parameters, such as cavity width, cavity height, squealer rim inclination, the number and orientation of squealer rims, etc. Gao Jie and Zheng Qun (2013) studied the rim layouts inside the cavity and found that the crosswise rims normal to the direction of the local leakage flow can effectively improve the aerodynamic performance. Prakash et al. (2006) found that the inclined pressure side rim could...
enhance the flow separation at the top of the rim and block the tip-leakage flow into the clearance. The study of Senel et al. (2018) shows that the increase of cavity height and cavity width could enlarge the sizes of the PSCV and the SSCV, enhancing the blocking effect. At present, although there are a lot of researches on the geometric parameters of cavity tip, no specific design method for squealer tips has been proposed. Moreover, the control mechanisms of various geometric parameters on tip-leakage loss are not explained clearly.

To propose a design method for cavity tip with certain guiding significance, two key geometric parameters of conventional cavity tips, the cavity width and cavity height, are studied by using numerical method in this paper. Based on the influence of cavity width and height on aerodynamic performance in a larger range of values, the optimal ranges of cavity width and cavity height are obtained, respectively. For several cases with obvious aerodynamic benefits, the axial distributions of the loss in the tip region are analyzed in detail, and the sources of aerodynamic benefits caused by cavity width and height are identified. The effects of the two geometric parameters on the evolution of the SV and the aerodynamic parameters of the tip-leakage flow are analyzed. Based on the relationship between the aerodynamic parameters of the tip-leakage flow and the loss, the controlling mechanisms of the cavity width and height on tip-leakage loss is clarified.

**METHODOLOGY**

**Research object and geometric parameters**

In this paper, a transonic single-stage high-pressure turbine is taking as the research object to investigate the effects of cavity width and height on tip-leakage flow with numerical simulation. The main aerodynamic and geometric parameters of the turbine are shown in Table 1. Flat tip and traditional squealer tip are studied in this paper. To get the effects of squealer geometric parameters on tip-leakage flow, the maximum cavity widths ($W$) of $9.2\tau$, $10.4\tau$, $11.0\tau$, $11.8\tau$, $12.5\tau$, $15.1\tau$, and the cavity heights ($H$) of $1.0\tau$, $1.5\tau$, $2.5\tau$, $3.0\tau$, $3.5\tau$ are studied. Figure 1 shows the geometric sketch of cavity tip with different cavity widths.

**Numerical methods**

The software ANSYS CFX19.0 is used to solve the steady compressible Reynolds average Navier-Stokes equations in the study. Previous study (Qi et al., 2010) shows that Shear Stress Transport (SST) turbulence model can accurately predict the aerodynamic performance and flow field details of turbomachinery. Therefore, SST turbulence model is employed in this study. The computational domain consists of a single stator channel and a single rotor channel. In the numerical calculation, total temperature, total pressure and turbulence intensity are used as the inlet boundary condition, and static pressure is used as the outlet boundary condition which can be adjusted to meet the total-total pressure ratio requirements of the turbine design state. Both surfaces at circumferential side of the computational domain are set as periodic boundary condition, the mixing-plane model is used at the interface between rotor and stator, and all the wall surfaces are set as adiabatic with no slip.

Domain meshes of the stator are generated by the software Autogrid5, and the domain meshes of the rotor are generated by the software ICEM CFD. The wall distance of the first mesh cell is set to 0.001mm, and the average calculated $Y^+$ is about 3. To avoid the unnecessary effects of different meshing methods on the numerical simulation results, all the cases use the same stator domain meshes and the same grid topology in the rotor domain. The whole computational domain and the grid details of the rotor tip are shown in Figure 2.

Grid independence validation is performed in this paper to prevent the insufficient grid density from affecting the accuracy of the numerical results. The turbine stage efficiency and the tip-leakage flow rate are investigated, as shown in Figure 3. When the grid number exceeds $2.72\times10^6$, the changes of the tip-leakage flow rate and turbine stage efficiency are negligible.
RESULTS AND DISCUSSION

Aerodynamic performance

Figure 4 shows the turbine stage efficiency of each case. It can be seen from Figure 4 (a) that no matter what the value of cavity width is, there is an optimal value range of cavity height, which is about 2.5-3.0τ. With the decrease of the cavity width, the effect of cavity width on the turbine stage efficiency is more significant. When the cavity width reaches ‘width5’, the turbine stage efficiency could be improved by about 0.14% by choosing the reasonable cavity height.

In Figure 4 (b), the variation of the turbine stage efficiency shows that there is also an optimal value of cavity width, which makes the aerodynamic performance best. The optimal value of cavity width is affected by the cavity height. When the cavity height is close to the optimal range, the optimal cavity width is about 10.0-10.5τ. In addition, the greater the cavity height, the greater the influence of cavity width on the turbine stage efficiency. When the cavity height is 3.5τ, the variation of the turbine stage efficiency caused by cavity width could be about 0.09%. It can be seen that the effect of cavity height on the turbine stage efficiency is more significant than cavity width.

Effect of cavity width

When the cavity height is 2.5τ, the aerodynamic performance of cases with different cavity widths are significantly different. Therefore, three cases with cavity width of ‘width 1’, ‘width 5’ and ‘width 6’ and cavity height of 2.5τ are selected for analysing the effect of cavity width on tip-leakage flow.

The dissipation function Φ represents the work term by the viscous force of fluid to resist the deformation, which irreversibly converts the mechanical energy of the fluid to the thermal energy. It can measure the local mixing loss caused by the viscous shear of fluid. In this paper, it is used to measure the loss caused by tip-leakage flow. The dissipation function can be calculated as the following formula:

$$\Phi = \frac{\mu_{eff}}{2} \left( \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \frac{2}{3} \mu_{eff} \left( \frac{\partial u}{\partial x} \right)^2$$  \hspace{1cm} (1)

The viscous dissipation function in the range of 50%-80% span is integrated at different axial position, and the result is shown in Figure 5 (a). It can be seen that the cavity width has little effect on the loss in the range of 50%-80% blade span. The only distinct variation appears at the 1.0-1.5 axial chord lengths downstream of the leading edge. When the
cavity width is less than the value of ‘width 5’, the loss in this axial region won’t change with the reduction of cavity width.

Figure 5 (b) shows the surface integral of the viscous dissipation function over 80% blade span. With the decrease of the cavity width, the loss in the channel increases slightly. However, the most significant loss variation occurs within the half of axial chord length downstream of the trailing edge. When the cavity width decreases from ‘width1’ to ‘width5’, the aerodynamic loss in this position decreases significantly. However, as the cavity width further decreases to ‘width 6’, the loss of this position increases slightly.

Figure 5 The surface integral of viscous dissipation function; (a): 50%-80% span; (b): over 80% span

According to the axial distribution characteristics of the aerodynamic loss, it’s almost certain that the loss differences caused by the variation of cavity width mainly result from the dissipation differences of the TLV downstream of the trailing edge. It can be seen from Figure 6 that the Mach number downstream of the throat drops sharply due to the effect of shock wave. The streamlines in the TLV core indicate that there is obvious backflow at this location. It is clear that the TLV is broken downstream of the shock wave.

The vortex breakdown is mainly affected by the adverse pressure gradient. Therefore, Figure 7 shows the isentropic Mach number distribution at 95% blade span, which reveals the effect of cavity width on blade loading. At the position of 0.5-0.645 axial chord length downstream of the leading edge, the pressure of suction surface decreases with the decrease of cavity width. At the position of 0.8 axial chord length, there is a strong adverse pressure gradient caused by shock wave, leading to the TLV breakdown. With the decrease of the cavity width, the position where the adverse pressure gradient appears moves downstream, but the adverse pressure gradient is intensified significantly.

Figure 6 Ma and streamlines in the tip region

The most significant characteristic caused by the TLV breakdown is the backflow in the vortex core. In order to obtain the location where the TLV breakdown occurs, the reverse flow regions of three cases are shown in Figure 8. The starting location, ending location and axial length of reverse flow regions are summarized in Table 2. In the case of ‘width5’, the reduction of the reverse flow region shows that the TLV breakdown is restrained. The variation of the starting location of the reverse flow region is consistent with the variation of the adverse pressure gradient in Figure 7. The delayed occurrence of strong adverse pressure gradient results in the corresponding delay of TLV breakdown. However, when the cavity width is over the value of ‘width 5’, the inhibiting effect of decreasing the cavity width on the TLV breakdown appears obvious marginal effect.
According to the above analysis, it could be sure that the reduction of loss at the position of 1.0-1.5 axial chord length in Figure 5 (b) is caused by the suppression of TLV breakdown. However, the mechanism of loss increase at the position of 0.5-1.0 axial chord length is not clear. Hence, it is necessary to further analyze the vortex evolution and loss distribution characteristics in the channel.

There are complex vortex structures, which have a significant effect on the tip-leakage loss, in the tip region. In order to gain further insight into the tip-leakage flow evolution and loss, it’s necessary to obtain a more accurate distribution of vortex structures by adopting the Liutex method (Liu et al., 2018). The Liutex method can eliminate the contamination caused by strong shear near the boundary layer (Wang et al., 2019).

Figure 9 shows the vortex structures inside the cavity identified by the Liutex method (Liutex=4×10⁴). The SV is the key vortex structure in the cavity, which has an aero-labyrinth liked sealing effect on the tip-leakage flow (Zou et al., 2017). ‘LineA’ in the figure is the location where the SV disappears in the cavity. Obviously, with the decrease of the cavity width, the chordwise length of the SV shortens significantly. The blocking effect of the region without the SV on the tip-leakage flow will decrease sharply.

It is worth mentioning that, with the decrease of the cavity width, the distance between the SV and the suction side rim in the front part of the cavity decreases obviously. The blocking effect of SV on tip-leakage flow is essentially caused by the interlocked labyrinth seal structure formed by SV, suction side rim and pressure side rim. As an aero-labyrinth tooth, the SV is close to the suction side rim, which is equivalent to the reduction of the spacing between labyrinth teeth, blocking the tip-leakage flow better. Therefore, with the decrease of the cavity width, the blocking effect of cavity on the tip-leakage flow in the front part of the cavity could be enhanced.

Figure 11 shows the distribution of the aerodynamic parameters of the tip-leakage flow along the streamwise direction. The definitions of clearance inlet and outlet surface are shown in Figure 10. Figure 11 (a) shows the distribution of leakage flow rate per unit area along the streamwise direction. The corresponding positions of the three troughs in the figure are exactly the positions where the scraping vortices disappear. Before the SV disappears, the distance between the SV and the suction side rim will decrease gradually, enhancing the blocking effect on the tip-leakage flow and diminishing the leakage rate. After the SV has disappeared, the sealing effect decreased sharply and the leakage rate increased rapidly. It can be found that at the upstream of 60% streamwise position, the leakage rate decreases with the decrease of cavity width. Figure 11 (b) shows the distribution of normal momentum of tip-leakage flow along the streamwise direction. Its distribution characteristics are similar to the leakage rate, also affected by the evolution of the SV. Therefore, it is proved that the decrease of the cavity width could enhance the blocking effect on the tip-leakage flow in the front section of the cavity.
Figure 11 Distribution of aerodynamic parameters of tip-leakage flow along the streamwise direction at the clearance outlet; (a): leakage rate per unit area; (b): normal momentum

Combined with the above analysis, theoretically, the mixing loss caused by tip-leakage flow should decrease with the decrease of cavity width, while the loss distribution at the position of 0.5-0.75 axial chord length in Figure 5 (b) shows that this is not the truth. In the further analysis, the loss inside and outside the clearance are distinguished, as shown in Figure 12. Thereinto, the loss inside the clearance is the surface integral of viscous dissipation over the region inside clearance shown in Figure 10. And the loss outside the clearance is the another part of the loss in the area above 80% span except the loss inside the clearance. It can be found that the mixing loss outside the clearance decreases with the decrease of cavity width, while the mixing loss inside the clearance increases significantly, resulting in the increase of the total loss in the channel at this axial region.

Figure 12 Distribution of loss inside and outside the clearance along the axial direction

Effect of cavity height

Three cases with cavity width of ‘width 5’ and cavity height of 1.0τ, 3.0τ, and 3.5τ are selected to reveal the influence mechanism of cavity height on tip-leakage flow and loss. Figure 13 shows the distribution of the surface integral of viscous dissipation function over 80% blade span along the axial direction. With the increase of cavity height, the loss in the range of 0.3-0.95 axial chord length has been decreasing. This indicates that the development of TLV in the channel is restrained and the corresponding loss is reduced. In the range of 1.0-1.5 axial chord length, when the cavity height is over the optimal value, the loss could increase with the increase of cavity height. The loss at this location is mainly resulted from the dissipation of the TLV downstream of the trailing edge. The increase of the loss indicates that the TLV would be enhanced near the trailing edge after the cavity height exceeds the optimal value.

The formation and development of the TLV in the early stage are mainly affected by the SV. The evolution of the SV inside the cavity is shown in Figure 14. With the increase of the cavity height, the size of the PSCV increases significantly, forcing the SV closer to the suction side rim, and the position where the SV disappears inside the cavity moves upstream. It can be found that the effect of cavity height on the evolution of SV is similar to that of cavity width.
In essence, the increase of the cavity height and the decrease of the cavity width result in the decrease of the spacing between aero-labyrinth teeth, enhancing the blocking effect on the tip-leakage flow.

The variation of loss in the range of 1.2-1.5 axial chord length may be caused by the development difference of the TLV near the trailing edge. Figure 16 shows the distribution of normal momentum of the tip-leakage flow along the streamwise direction. At the downstream of 62% streamwise position, the momentum increases significantly with the increase of cavity height. At this streamwise position, there is no SV in the cavity, and the blocking effect on the tip-leakage flow is weak. Moreover, the fluid inside the PSCV flows out near the trailing edge, increasing the momentum of the local tip-leakage flow. The size of the PSCV and the fluid carried by it are significantly affected by the cavity height, so is the momentum of the tip-leakage flow near the trailing edge.

**CONCLUSIONS**

In this paper, the effects of cavity height and cavity width on tip-leakage flow and loss are studied, and the mechanism is revealed.
Firstly, there is an optimal value for both the cavity height and the cavity width. The optimal value of cavity height is 2.5-3.0τ. The optimal value of cavity width is affected by the cavity height and is about 10.0τ-10.5τ when the cavity height is near its optimal value. Secondly, the effects of cavity width and cavity height on the evolution of the SV are similar, but the two geometric factors have opposite effects on the loss inside the clearance. Thirdly, the aerodynamic benefits resulted from the increase of the cavity width mainly come from the suppression of the TLV breakdown, but it is also affected by the adverse changes of the tip-leakage loss in the channel. Fourth, the variation of the loss inside the clearance is the main influence caused by the cavity height differences, and accounts for 80% of the loss in the tip region of 0.3-0.9 axial chord length.

**NOMENCLATURE**

- $H$: cavity height, m
- $Ma_{exit}$: relative Mach Number at the rotor exit
- $Ma_{is}$: isentropic Mach Number
- $Re_{exit}$: relative Reynolds Number at the rotor exit
- $t_p$: width of pressure side rim, m
- $t_s$: width of suction side rim, m
- $u_i$: $u, v, w$, velocity component, m/s
- $x_i$: $x, y, z$, coordinate, m
- $\mu_{eff} = \mu + \mu_t$: effective viscosity, dynamic viscosity and eddy viscosity, kg/(m∙s)
- $\pi$: total-to-total pressure ratio
- $\tau$: clearance height, m
- $\Phi$: viscous dissipation function, J/(s∙m$^3$)
- $\omega_S$: streamwise vorticity, 1/s

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