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Aerothermal Investigation of Transonic Over-Tip Leakage Flow with Cooling Injection for Different Tip Geometries

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ABSTRACT

Complex interactions between Over-Tip Leakage (OTL) flow and cooling injection have been the focus in turbomachinery. In the present work, a numerical investigation was carried out for such interactions between the transonic OTL flow and cooling injection with the quasi-three-dimensional (Quasi-3D) models employed. The results show that, for the flat tip, the nondimensional scale of separation bubble is pretty much constant. For the squealer tip, the interaction between cooling injection and OTL forms a counter-rotating vortex pair (CRVP), and the thermal stripes on the suction side (SS) rim are mainly caused by the interaction between OTL and CRVP. For the given cooled flat and squealer tips, the flow was blocked by cooling injection, and which may reduce the overall OTL mass flux. Further research revealed that this blocking effect was related to the cooling hole location and orientation. Three-dimensional numerical simulations provide further validation for those conclusions.

INTRODUCTION

In modern turbomachinery, the blade tip of the high-pressure turbine (HPT) becomes one of the most vulnerable areas due to the high thermal load. The flow passing through the tip clearance between the blade tip and the casing also leads to the flow loss, namely, the OTL flow loss. It decreases the turbine efficiency. Therefore, heat transfer and aerodynamics need to be comprehensively considered to design qualified blade tips of HPT.

Experimental studies have been extensively carried out to investigate the heat transfer and aerodynamic performance on the tip regions. Detailed heat transfer coefficient and static pressure distributions on different tip geometries were measured by Azad et al. (2000a, 2000b) by utilizing the transient liquid crystal technique. Kwak et al. (2003), Kwak

and Han (2002a, 2002b) analysed the effects of tip gap heights, turbulence intensity and Reynolds number on the heat transfer in the tip regions of both flat and squealer tips. Christophel et al. (2005a, 2005b) experimentally investigated the effect of the pressure side (PS) blowing on the heat transfer coefficients and the adiabatic effectiveness levels. Using the 2D-PIV technique, Hu et al. (2014) reported that a good leakage control effect only happened on the condition of a small tip gap and the medium blade load. Zhang et al. (2011) showed that the heat transfer over the turbine blade tip is greatly influenced by the shock wave structure within the tip gap. After multiple reflections of shock waves, the supersonic flow finally ended with a normal shock. A strong interaction between heat transfer and aerodynamics for transonic turbine blade tips was discussed by Zhang and He (2014) as well. Hofer and Arts (2009) found that the effect of cooling on the overall mass-weighted loss coefficient was marginal for the double squealer geometries investigated in their transonic experimental study.

Lots of numerical calculations have also been conducted to study the aerothermal characteristics. The effects of different tip geometries, including flat tip, double squealer tip, and suction side squealer tip, were numerically studied by Krishnababu et al. (2007). Their results illustrated the OTL mass flow rate and heat transfer to the tip increased with the increase of tip gap height. The effects of relative casing motion and cooling injection on the flow and heat transfer performances of the OTL flow were investigated by Krishnababu (2007) and Newton et al. (2009) as well. Similar researches were conducted by Yang et al. (2006, 2013). The simulation results showed that the heat transfer weakened with increasing cavity depth, and the shallow cavity is the most effective tip geometry to decrease the overall heat load. The effects of tip gap clearance and casing recess on the heat transfer and the stage efficiency for many

squealer blade tip geometries were studied by Ameri et al. (1999). It was observed that introducing the recessed casing resulted in a drop in the rate of heat transfer on the pressure side. There existed a marked reduction of thermal load and peak value on the blade tip dropped dramatically. Furthermore, Ameri and Bunker (1999) implemented a computational study to investigate the detailed heat transfer characteristics on the blade tip surfaces for a high-power turbine, and the numerical results were compared with the experimental data of Bunker et al. (1999). Cheng et al. (2017) studied the effects of film hole location on squealer tip leakage flow, film cooling effectiveness, and surface heat transfer coefficient. The effect of trailing edge cutback on squealer tips was numerically investigated by Cheng et al. (2016). Research results showed that the trailing edge cutback on both the suction and pressure side of the squealer tips could increase the leakage mass flow rate. The influence of injection angle and blowing ratio on the leakage flow, aerodynamic efficiency, and the film cooling efficiency was simulated by Cheng et al. (2016).

Ahn et al. (2005) studied the film cooling effectiveness of different tip geometries, tip clearance heights, locations of the cooling holes, and blowing ratios. Similar studies had been conducted by Mhetras et al. (2006) as well. The blockage effect caused by cooling injection were investigated by many researchers such as Niu and Zang (2011), Curtis et al. (2009), Couch et al. (2005), and Hohlfield et al. (2005). Wheeler and Saleh (2013, 2011) studied the effect of adding cooling slot to flat and squealer tips in transonic OTL flow condition. Their results consistently showed that there was a potential to reduce tip leakage loss by tip cooling. Experimental and numerical results obtained by Ma et al. (2016a, 2016b) demonstrated that when the cooling injection was introduced, the distinctive thermal stripes were observed on the squealer cavity floor and on the SS rim.

The present numerical study concerns the flow and heat transfer on the blade tip regions with two different tip geometries including a flat tip and a squealer tip. A series of quasi-three-dimensional simulations have been conducted to investigate the strong interactions between transonic OTL flow and cooling injection. A part of the computational results is compared to the experimental results of Ma et al. (2016a, 2016b). Furthermore, three-dimensional computational results have been analysed to validate the previous conclusions.

NUMERICAL METHODS

The commercially available CFD solver, ANSYS-CFX, was used to conduct the present computational simulations. The results were obtained by solving the steady Reynolds-averaged Navier-Stokes (RANS) equations. Both the Spalart-Allmaras model (SA) and the Shear Stress Transport $k-\omega$ turbulence model (SST) were selected to conduct the grid independence verification and the results were compared to the experimental results. Employing the ICEM software generated all structured meshes.

Figure 1 Computational domain and mesh

Computational model and mesh

In order to better investigate the detailed features of leakage flow inside the tip clearance, a kind of simplified model, so-called quasi-3D model, was cut from the full 3D passage. The same research method had been utilized by Wheeler et al. (2013) and Wang et al. (2015). Figure 1 shows the 3D computational domain and meshes, and the quasi-3D fluid domain is also presented. The same 3D blade profile was used by Ma et al. (2016a, 2016b).

Figure 2 Geometric parameters of quasi-3D computational model

The geometric parameters of the quasi-3D computational model are shown in Figure 2. The gap gap sizes of the flat and the squealer tips are set to 0.675 mm, the same as that in full-3D blade model. The passage height equals to 25 times of tip gap, which makes the influence of the hub negligible. The total length of the passage in flow direction was 4.0 times of the span between pressure side and suction side, as shown in Figure 1, the frontal part ahead of the blade accounts for one-fourth of the total length.

Boundary Conditions and Setup

For the 3D and quasi-3D computational domains, the total pressure ($P_{0,in} = 180 \text{ kPa}$) and total temperature ($T_{0,in} =$

300 K) are set in the cascade inlet. The static pressure of 101 kPa is given at the exit of the passage. The hub is specified as a symmetric boundary. Two domain interfaces in the circumferential direction are translational periodic boundaries. Similarly, the total pressure ($P_{0,coolant}/P_{0,in}=1.1$) and total temperature boundary are specified to the coolant inlet. In order to acquire the heat transfer coefficient (HTC), the no-slip isothermal boundary conditions in two specific temperature (280K and 290K) are respectively set to all walls. The ratio of wall heat flux difference to temperature difference is HTC. Similar boundary conditions were employed in Ma et al (2016a, 2016b).

Like the full 3D computational domain, the structural mesh is utilized in the quasi-3D domain. The growth rate of boundary layer grids is set to 1.1 to simulate the real flow.

Grid Independence Study

More details of the grid are illustrated in Table 1. With the increase of grid points within tip and cavity heights, the number of grid elements fluctuates from 3.65×10^6 to 6.97×10^6 . Meanwhile, the average y^+ value on tip surfaces slightly grows. In general, it is around 0.8 for both SA and SST models.

Table 1 Grid details of 3D computational domains

Grid Number(million)		3.65	4.70	5.74	6.97
Grid Points within Tip Gap	SA/ SST	20	30	40	50
Grid Points within Cavity Height	SA/ SST	30	40	50	60
Average y^+ on Tip Surfaces	SA	0.7687	0.7782	0.8190	0.8273
	SST	0.8096	0.8070	0.8047	0.8039

Figure 3 Averaged HTC on Tip Surfaces of different grid numbers

As shown in Figure 3, when the total number of grid nodes inside the tip gap and the cavity height increases from 50 to 90 (the total grid elements from 3.65×10^6 to 5.74×10^6), the average value of HTC on tip surfaces undergoes a big alteration relatively. However, no more considerable change happens for the average value of HTC when the total grid elements further grow into 6.97×10^6 .

Figure 4 displays the distributions of relative HTC difference among the different grid quantity. The relative HTC difference between 3.65×10^6 and 4.70×10^6 elements is large. For the case (b), it also shows a similar distribution of HTC difference except for the rim region and the surface

near trailing edge. In comparison, the relative HTC difference between 5.74×10^6 and 6.97×10^6 elements is less than 1.5% totally. It means that although more nodes are added to the tip gap and cavity height, the influence of grid number will be negligible. Therefore, 5.74×10^6 elements are chosen to develop the current computational investigation.

Figure 4 Distributions of relative HTC difference among the different grid quantity (a) 3.65 and 4.70 million (b) 4.70 and 5.74 million (c) 5.74 and 6.97 million

Turbulence Model Validation

Compared with the experiments (Ma et al.,2016a), the results of CFD simulation using SST model and SA model show significant differences about the HTC distributions on the blade tip surfaces.

As shown in Figure 5, both SST and SA models are in great agreement with the experimental results globally, especially for the high HTC regions on the rim surfaces near the leading edge and the low HTC regions on cavity floor near the pressure side. The HTC distributions on the rim surface near the SS, by comparison, is more continuous and uniform for SA model. However, the SST model apparently shows a better prediction on the high HTC regions than the SA model over the cavity floor and that explains the good accuracy of SST model in solving the near-wall flow. Moreover, the quasi-3D computational domain was cut from the location of maximum inscribed circle that is located in the high HTC region near the leading edge. Therefore, the SST model shows a comprehensive advantage in quasi-3D calculations and it has been chosen in the present study.

Figure 5 Contours of HTC on the blade tip surfaces using SST k- ω model and SA model compared with Experimental results

RESULTS AND DISCUSSIONS

Aerodynamic Performance of Quasi-3D Cases

Effect of Gap Size on Uncooled Flat Tip

To probe the aerodynamics of OTL flow for the flat tip with different tip gap heights, the total pressure loss coefficient, ζ , along the domain midplane of the flat tip is shown in Figure 6. Three different tip gap heights, including 0.5%, 1.0% and 1.5% of the blade span, are considered in the present work. It is observed that the flow separates when the fluid enters the corner of pressure side, and then reattaches after an appropriate distance. There exists a separation bubble on the blade tip surface near the PS. Note that the total pressure loss coefficient is relatively big against other parts for each case. That also means the smaller velocity in this region. The averaged total loss coefficient raises with the increase of tip gap height, and the most value of loss coefficient ζ occurs in the case of 1.5% blade span than the other two cases.

Figure 6 Total pressure loss coefficient on the mid-plane of computational domain three different tip gap heights (a) 0.5% blade span (b) 1.0% blade span (c) 1.5% blade span

In order to further explore the mechanism of over-tip leakage flow and describe the relative size of separation bubbles, the coefficients of contraction in different cases (0.5%, 1.0%, 1.5% blade span) are revealed in Figure 6 and Table 2. If the minimum distance between specific isosurface of $\zeta = 1.0$ (around the separation region) and the casing is recorded as h , the coefficient of contraction σ is defined as the ratio of the minimum distance h to tip gap height, namely

$$\sigma = \frac{h}{g} \quad (1)$$

TABLE 2 Coefficients of contraction and scale of flow separation region

Cases	Tip gap heights of $g(\text{mm})$	Maximum distance between isosurface of $\zeta = 1.0$ and tip surface($\text{mm})$	Coefficients of contraction σ
0.5% blade span	0.3375	0.0541	0.8397
1.0% blade span	0.6750	0.1199	0.8224
1.5% blade span	1.0125	0.1745	0.8277

Obviously, it is seen that an increase of tip clearance expands the range of separation region. Although the maximum distance between isosurface of $\zeta = 1.0$ and casing differs a lot for those three cases, the distinction of the coefficient of contraction is pretty slight.

Effect of Cooling Injection

After introducing the cooling jet hole (the inclination angle is specified as 45° , 90°) into the flat tip, the comparison map of Mach number distributions on the midplane of the quasi-3D channels are shown in Figure 7. For the uncooled flat tip, the flow choking occurs within the casing and flow separation region. However, the flow in the same locations for cooled tip cases is subsonic and the flow is choked close to the downstream corner and adjacent casing of the exit of the cooling hole.

Figure 7 Mach number distributions on the mid-plane of the computational domain for uncooled and cooled flat tips

Utilizing an isosurface of fluid stagnation pressure (with the expression of $P_{0,c}/P_{0,in} = 1.03$), the cooling jet core is vividly presented in Figure 8(a). Mach number distributions are displayed on such isosurface and streamlines as well. The coolant ejecting from the cooling hole (perpendicular to the tip surface) bends in the direction of leakage flow and bifurcates into two branches affected by the upstream fluids and casing. There exists a locally symmetrical high Mach number region on the isosurface near the exit of the cooling hole. It illustrates that the flow is in supersonic state, which differs a lot from the location of high Mach number regions for the uncooled flat tip. Compared with the uncooled flat tip, the streamlines inside the tip gap for the cooled flat tip are more disorderly due to the mixing of coolant and leakage flow. It indicates the flow field of the latter is more complex.

Figure 8 The sketch of the flow field within the tip gap for the cooled flat tip: (a) streamlines and cooling jet core coloured by Mach number (b) Mach number distributions and surface streamlines along three cut-planes

Figure 8(b) shows the Mach number distributions along three cut-planes downstream of the cooling hole. A large choking region could be observed on the plane adjacent to the cooling hole exit. The coolant ejected from the hole causes such a strong blockage effect. It also produces a two kidney-shaped low Mach number zone. A CRVP is clearly visible on the cut-planes as the detailed features of surface streamlines are shown.

Figure 9 intuitively plots the Mach number contours with streamlines along the domain midplane for cooled squealer tips. The cooling holes (including inclination angle of 45° , 90°) seated at various locations are studied. It is found that there exists a large recirculating vortex inside the groove for uncooled squealer tip. More small vortices are formed with the introduction of cooling injection. Note that the flow, compared with the uncooled case, turns to be subsonic within the tip gap near PS. While the flow is still in transonic state over the tip region near SS.

Figure 9 Mach number distributions on the mid-plane of the computational domain for uncooled and cooled squealer tips

Figure 10 presents the nondimensional OTL mass flow rate at the entry and exit of tip gap for different locations of cooling holes, and two injection angles ($\alpha = 45^\circ$, $\alpha = 90^\circ$) are investigated for both the cooled flat tips and the cooled squealer tips. With the introduction of cooling injection, both $\alpha = 45^\circ$ and $\alpha = 90^\circ$ show a great reduction of OTL flow at the entry and the exit of the tip gap. As is shown in Figure 10(a), for the case of $\alpha = 45^\circ$, the maximum reduction of entry mass flow rate approaches 71% when the cooling jet hole is located in the case of $x/c = 0.25$. It indicates the blockage effect caused by cooling injection is pretty strong. Meanwhile, the overall OTL mass flow rate at the exit of is relatively small despite the strong cooling injection. Similarly, both the maximum reduction of entry and exit mass flow rate occurs in the case of $x/c = 0.25$ when the injection angle turns to be 90° .

For the cooled squealer in Figure 10(b), in comparison, the entry mass flow rate decreases more than the exit mass flow rate does. It reveals that the coolant injecting from the cooling jet hole accounts for a considerable proportion of the overall OTL flow, which differs a lot for the cooled flat that is observed in Figure 10(a). Note that the non-dimensional OTL mass flow rate for the case of $\alpha = 45^\circ$, whether it is at the entry or at the exit, declines most heavily for the case of $x/c = 0.25$. Similar conclusion could be reached as the injection angle is 90° . It is observed that the entry and exit

mass flow rate in case of $\alpha = 45^\circ$ is close to that in case of $\alpha = 90^\circ$ once the cooling hole is fixed. For the given cases, it is found that the blocking effect for the cooled flat tip is greatly affected by the change of inclination angle (from 45° to 90°), however, the cooled squealer tip is insensitive to this change, it is because the coolant firstly impinges into the groove and is less directly affected by the leakage flow. The optimal layout of cooling hole should be placed at the location of $x/c = 0.25$ to lower the OTL flow better for both the cooled flat tip and squealer tip.

Figure 10 Nondimensional OTL mass flow rate at the entry and exit of the tip gap for different locations of cooling hole (45° and 90° injection angles included)

Figure 11 illustrates OTL flow structures on a cross section (cut along the middle of rim) near the suction side and the corresponding HTC contours (Figure 11(d), (e) and (f)) on the blade tips. The effects of three diverse locations of cooling holes, perpendicular to the cavity floor, are investigated. The flow within the tip gap near the suction side is in choking condition as it reaches a sonic state. Mach numbers are almost symmetrically distributed on the cut-planes, and shape of the low-Mach number region is large in the middle and small on both sides. It seems to be due to the altering of the initial flow separation structure, the CRVP exerts upward traction to the low-momentum flow near separation boundary in the middle part of the cut-plane and downward pull to the high-momentum flow on both sides. And this effect is getting sharper when the cooling hole gets closer to the cross section. Note that the local HTC over the rim surfaces (within black dotted lines) are symmetrically distributed, and heat exchange gets stronger on both sides as

the cooling hole approaches the suction side. This trend could be explained by the change of the OTL flow structures in Figure 11(a), (b) and (c).

Figure 11 OTL Flow structures on a cross section over the SS rim and the HTC distributions over the blade tips

Figure 12 further elaborates the characteristics of OTL flow with cooling injection, and the CRVP painted by the spanwise velocity (V_z) is displayed. As shown in Figure 12(a), the flow within the tip gap is choked and the profile of separation region in mid-plane is larger than that in another cut-plane. It exactly corresponds to the results in Figure 11. The coolant injecting from the cooling jet hole, similar to the cooled flat tip, bifurcates into two branches. With the downward velocity ($V_z < 0$), the peripheral flow of the vortex pair oppresses the flow coming from the upstream OTL flow. As Figure 12(b) indicates, a big portion of OTL flow is squeezed into the middle of the domain's cross section. Those OTL flow gradually expands upward with the upward pull.

Figure 12 Detailed flow structures of cooled squealer tip including (a) Mach number contours along two cut-planes; (b) interactions between coolant and OTL flow; and (c) the counter-rotating vortex pair coloured by spanwise velocity

Aerothermal Characteristics of Full 3D Blades

Figure 13 shows the overall OTL flow structures on blade tip surfaces for the cooled flat and the squealer cases. The streamlines of upstream fluid and coolant are in red and blue respectively.

Figure 13 Overall OTL flow streamlines for cooled flat and squealer cases

Affected by the casing and the upstream fluid, the coolant for both cooled flat tip and cooled squealer tip bifurcates into two branches. This is consistent with the analysis in quasi-3D cases. However, for the squealer tip, a wider diffusion range of coolant is observed for the hole in the same location comparing to the flat tip. As the white dashed lines show, note that a portion of fluid flows to the bottom of the coolant. This part usually locates between the adjacent CRVPs. However, the other part is lifted with an upward pull and that also explains the existence of the thermal stripes over the blade tips in Figure 14(b), especially in the downstream of the coolant and the surface of SS rim (the yellow elliptical region near suction side in Figure 13). Another observation is that there exists a vortex in the frontal part near the leading edge in Figure 13(b). The fluid firstly flows towards the suction side, and then it is reflected by the SS rim and a recirculation region appears. Along the direction of the mainstream, the vortex is formed finally.

Figure 14 compares the HTC on different blade tip surfaces, and the uncooled/cooled cases for flat and squealer tips are investigated. For all displayed cases, an evident ridge of high HTC is observed near the leading edge (marked A). The flow there, driven by the pressure from the mainstream, separates and then reattaches (see the leading edge in Figure 13). Similar to the region A, a stripe of high HTC is presented along the edge near the pressure side. For the cooled flat tip, note that there exists a stripe of low HTC near region B. The profile of this striped low HTC region is in accordance with the border of the normal shock wave. Similar conclusions have been reported by Zhang et al. (2011) and Zhong et al. (2013).

Compared with the uncooled cases, a distinct change of HTC distributions occurs over the tip surfaces, especially in the area around the cooling holes and the downstream of such holes. For the cooled flat tip in Figure 14(c), high HTC stripes are distributed on the downstream surfaces (marked

C). Obviously, the left side of those stripes undergoes stronger heat transfer than the right side, which differs a lot from the symmetrical distributions for the quasi-3D cases. This also illustrates, over the tip surface, the right leg of CRVP is more dominant than the left leg. Similar study is reported by Ma et al. (2016b). For the cooled squealer tip, A relatively low HTC region appears along the camber line (marked D) in Figure 14(d). On both sides of such a line, high HTC areas are discretely and asymmetrically distributed. Meanwhile, a series of thermal stripes could be observed on SS rim (marked E). A similar to the conclusion for the quasi-3D cases, a closer distance between the cooling hole and SS rim leads to a stronger process of heat transfer over the SS rim. And All of which indicates a strong effect on heat transfer characteristics from the aerodynamics.

Figure 14 Comparison of HTC on different blade tip surfaces: (a) uncooled flat tip; (b) uncooled squealer tips; (c) cooled flat tip; and (d) cooled squealer tip

CONCLUSIONS

It is observed that an increase of tip clearance expands the scale of separation region for the uncooled flat tip. Although the maximum distance between isosurface of $\xi = 1.0$ and casing differs a lot for the given three flat tips (0.5% blade span, 1% blade span and 1.5% blade span), the non-dimensional scale of separation bubble is pretty much constant.

The coolant firstly hits the casing and then bifurcates into a CRVP in the downstream of cooling holes. A portion of upstream OTL flow is squeezed into the middle of vortex pair and is lifted with the upward pull by such CRVP, the other part flows to the bottom of the coolant. This causes the thermal stripes over the surfaces of blade tip and rim for both quasi-3D and 3D computational domains.

It is found that the blocking effect for cooled flat tip is greatly affected by the change of inclination angle (from 45° to 90°), however, the cooled squealer tip is insensitive to this change. For given cooled flat and squealer tips, the optimal layout of cooling hole should be placed at the location of $x/c = 0.25$ to better reduce the overall OTL flow.

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NOMENCLATURE

- c = length of two inwalls of rims (mm);
- CRVP = counter-rotating vortex pair
- d = cooling hole diameter (mm);
- EXP = experiment;
- g = tip clearance height (mm);
- h = minimum distance between isosurface of $\xi = 1.0$ and casing (mm);
- HPT = high pressure turbine;
- HTC = heat transfer coefficient;
- l = depth of squealer cavity (mm);
- $\dot{m}$ = mass flow rate (kg/s);
- OTL = over-tip leakage;
- P = pressure (Pa);
- PS = pressure side;
- s = length between pressure side and suction side (mm);
- SS = suction side;
- t = width of squealer rim (mm);
- V = velocity (m/s), vortex;
- w = pitch of quasi-3D computational domains (mm);
- x = distance from inwall of rim near PS to centre of cooling hole (mm);
- α = injection angle ($^\circ$);
- ξ = total pressure loss coefficient, $(P_{0,in} - P_0) / (P_{0,in} - P_{exit})$.

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