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Experimental Study of Effects of Tip Geometry on the Flow Field in a Turbine Cascade Passage

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This study investigates the effects of blade tip geometry on the flow field of a turbine cascade at the incidence angle of 0 degree experimentally. The tests were performed in a low-speed turbine cascade wind tunnel. The Reynolds number based on the blade chord was about 172300 at the exit. Traverses of the exit flow field were made in order to measure the overall performance. The effects of using flat tip and grooved tip with a chord-wise channel were studied. The case with the flat tip is referenced as the baseline. The tip clearances are all 1 mm measuring 0.84 percent of the blade span. The depth of channel is 2mm.The flow field at 10% chord downstream from the cascade trailing edge was measured at 38 span-wise positions and 26 pitch-wise positions using a mini five-hole pressure probe. The static pressure distribution on the tip end wall is measured at 16 pitch-wise stations and 17 chord-wise stations. Results show that there exists great pressure gradient in the pressure side for the flat tip and the pressure side squealer tip, which means strong leakage flow. The pressure gradient from the pressure side to the suction side is greatly decreased for the grooved tip, and the resulting leakage flow is weaker. The core of the leakage vortex moves closer to the suction side for the pressure side squealer tip and farther away from the suction side for the suction side squealer tip. The pressure side squealer has little advantages over the flat tip in improving the flow capacity and reducing the overall losses. The suction side squealer tip and grooved tip can effectively decrease the intensity of the tip leakage vortex, improve the flow capacity and reduce loss of the turbine cascade passage and the grooved tip performs the best.

Keywords: blade tip geometry, turbine cascade, flow field, effect

Introduction

Because of the pressure difference between the pressure and suction sides of the blade, there exists a strong leakage flow through the clearance which exists between the rotor blade tip and the casing wall. The tip leakage flow has a significant effects on the loss production, aerodynamic efficiency and thermal performance of gas turbines. For example, losses due to the leakage flow can account for as much as one third of the losses in a turbine stage[1]. Also, high heat transfer rates resulted from high velocity in the gap flow have been a source of "burnout" of turbine blades[2].

There are two different and equally important aspects to tip leakage flows[3]. First, there is a reduction in the blade force and the work done. This occurs because the

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Nomenclature

c	chord (mm)	V_s	streamwise velocity(m/s)
C_d	discharge coefficient	V_{inlet}	velocity at inlet(m/s)
C_{ps}	$(P_s-P_{s0})/(P_{t0}-P_{s0})$, static pressure coefficient	**Greek letters**	
C_{vs}	V_s/V_{inlet}, streamwise velocity coefficient	β_1	inlet flow angle(°)
p	pitch(mm)	β_2	outlet flow angle(°)
P_s	static pressure at outlet(Pa)	ω	$(P_{t0}- P_t)/(P_{t0}-P_{s0})$, total pressure loss coefficient
P_{s0}	static pressure at inlet(Pa)	**Subscripts**	
P_t	total pressure at outlet(Pa)	1	inlet
P_{t0}	total pressure at inlet(Pa)	2	outlet

leakage flow passes over the blade tip without being turned. The second major aspect is the subsequent mixing of the tip leakage flow with the main passage flow. This causes significant aerodynamic loss.

Lots of studies have been done to investigate the tip leakage flow development and the resulting aerodynamic loss. A.Yamamoto[4][5] studied the loss generation mechanisms due to the tip leakage flow in turbine rotor passages by measuring three dimensional flows in a low speed linear turbine cascade for various tip clearance sizes and for various inlet flow angles. They found that the incidence variation significantly affects the secondary flow and the associated loss fields downstream of the cascade, while the leakage vortex is less sensitive to the incidence variation than the passage vortex. The reason is that most of the leakage flow that forms vortex occurs at the rear part of the tip. Moreover, the leakage flow tends to follow the pressure gradient within the gap at small clearance gap. As the gap size increases , the inertial force of the inlet end-wall flows appears to become an important factor in determining the leakage flow vectors in the front part of the tip.

J.P.Bindon[6] measured detailed development of tip clearance loss from the leading to the trailing edge of a linear turbine cascade and quantified loss contributions made by mixing, internal gap shear flow , and end-wall secondary flow. They showed that internal gap loss made up 39 percent of the total, suction corner mixing loss formed 48 percent, and end-wall /secondary loss the remaining 13 percent.

M.Yaras et al.[7]reported the measurements of the flow in the tip gap of a planar cascade of turbine blades for three clearances. It has also been shown that the fairly complicated flow can be predicted well using a relatively simple model. M.Yaras et al.[8]made detailed measurements of the tip leakage flow downstream of a planar cascade. The results give insight into the size and strength of the leakage vortex in relation to the size of the tip gap and the evolution of vorticity as the vortex diffuses laterally downstream of the blade row. Also, it was found that the vortex could be modeled with a simple model based on the diffusion of a line vortex.

P.T.Dishart et al.[9] made an investigation of tip leakage flow and its effects on loss production on a large scale linear turbine cascade. They measured the flow exiting the tip gap and the flow downstream the blade trailing edges and calculated the overall tip leakage loss, loss already produced by the tip gap exit, secondary kinetic energy associated with the tip gap exit flow and the loss produced by the dissipation of this secondary kinetic energy.

Denton[10] developed a tip loss model. As can be concluded from the model, there are several possible means of reducing the over tip leakage flow related loss, at given relative tip clearance level t/h, pitch-chord ratio s/c, relative exit velocity V_2 and relative exit angle β_2.

Reducing the discharge coefficient C_d is one of the means of reducing the tip leakage flow related loss. Several studies have been done to explore this method.

Bindon and Morphis (1992)[11] have reduced the losses generated within the tip gap by radiusing the blade pressure side tip corner, thus removing the separation bubble, and by contouring the blade tip to form a suction side squealer. The overall losses generated within the cascade, however, were not found to be simply related to the losses generated within the gap.

McGreenhan and Schotsch (1988)[12] found that the rounding of pressure side corners can increase the size of the contraction coefficient of the blade tip gap. By doing so, the losses in the tip gap are reduced. But at the same time, the discharge coefficient is enhanced and it is this which determines the overall losses at cascade exit.

F.J.G.Heyes et al.(1992) [13] investigated the effect of using plain tips, suction side squealers and pressure side squealers on the tip leakage flow in axial turbine cascades. In linking the tip discharge coefficient and cascade losses, a model is developed for predicting the relative performance of tip geometries. As can be seen from the model, for a particular cascade at a single clearance, the overall losses at cascade exit varied with the discharge coefficient C_d, while the losses generated within the tip gap varied with $C_d(1-C_d^2)$. In another word, for a given blade, it is the discharge coefficient that primarily determines the overall cascade loss.

Cengiz Camci et al. (2005)[14] experimentally investigated the aerodynamic characteristics of full and partial-length squealer separately on the pressure side and on the suction side in an axial flow turbine stage. They changed streamwise length of partial squealer tips and their chordwise position to find an optimal aerodynamic tip configuration. The results show that partial squealer tips in axial flow turbines 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.

C.Prakash et al. (2006)[15] numerically investigated squealer tip with vertical shelf and inclined shelf near the pressure side. The results showed that the inclined shelf can reduce the leakage flow and improve efficiency.

The present experiments were performed in a low-speed cascade wind tunnel of BeiHang University. This paper experimentally investigates the effects of three different tip geometries on the flow field of a turbine cascade. The flat tip is studied as baseline case .

Experimental Facility and Test Technique

Fig.1 shows a general view of the linear cascade wind tunnel in BeiHang University. The exit rectangle of the tunnel is 250mm×120mm. The inlet boundary layers on the end wall are less than 3mm and the inlet turbulence intensity is 4%. The inlet flow angle can be varied by replacing the joint section installed upstream the cascade section. The cascade has a tailboard to adjust periodicity among the blade passage flows.

As can be seen in Fig.1, the central three blades have a tip gap on the top end. On the other hand, the blade #1 and #5 are attached to the top and bottom walls and as a result no tip gaps remain for the two blades.

Based on the diagram of basic parameters of the linear cascade shown in Fig.2, the major specifications of the cascade are given in Table 1.

The flow field downstream was measured using mini five-hole pressure probe as shown in Fig.3. The pressure probe has a conical head with a diameter of 2 mm. The measurement error of the probe is calculated including displacement error, sensor error, error of data collection platform. Angle error is less than 0.3 degree, and the total pressure error is less than 0.5 percent.

PXIe data collection platform and data acquisition card PXI6225 are used. It has 80 channels and the highest single channel sampling rate is 250 kHz.

The flow field at 10% chord downstream from the cascade trailing edge was measured at 38 span-wise positions and 26 pitch-wise positions using a mini five-hole pressure probe. The position of the traverse plane downstream of the cascade is shown in Fig.2. The static pressure distribution on the tip end wall is measured at 16 pitch-wise stations and 17 chord-wise stations. The measuring stations at the outlet and on the end wall are shown in Fig.4.

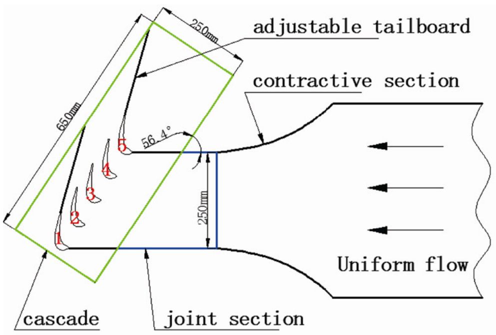


Fig. 1 Overall view of the turbine cascade wind tunnel

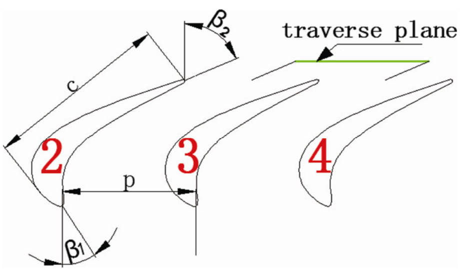


Fig. 2 Diagram of basic parameters of the linear cascade

Table 1 Cascade geometry and test conditions

Tested turbine cascade		
Number of blades	N	5
Chord	c	102mm
Span	s	119mm
Sodility	c/p	1.36
Inlet flow angle	β_1	33.6°
Outlet flow angle	β_2	67°
Reynolds No. (based on exit velocity and chord)	Re	1.7×10^5

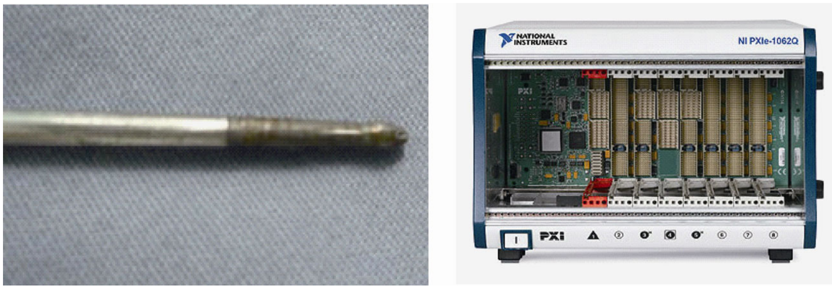


Fig. 3 Five-hole probe and PXIe data collection platform

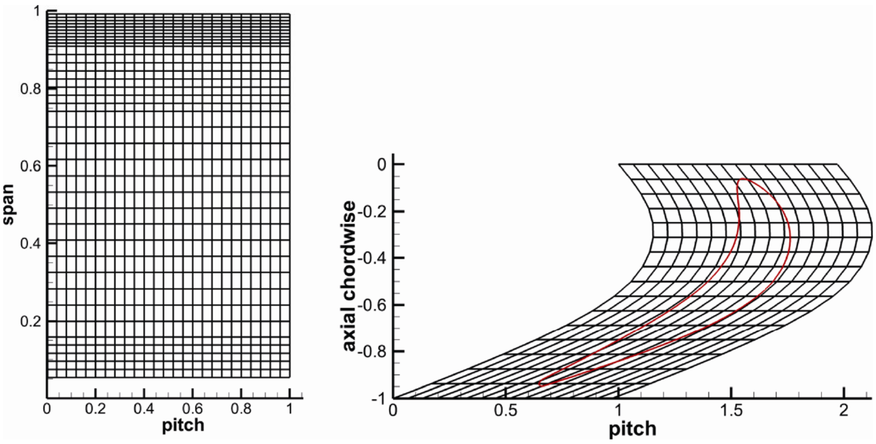


Fig. 4 Measuring stations at the outlet and on the tip end wall

Experimental Results and Discussion

Three different tip geometries are investigated, and the flat tip is studied as baseline case. The set of tip geometries are defined in Fig.5. Flat tip is shown in Fig.5(a), which acts as baseline. Fig.5(b) and Fig.5(c) show the pressure side squealer tip and the suction side squealer tip respectively. Fig.5(d) shows the grooved tip, which has a chord wise channel on the blade tip. The tip clearances are all 1 mm. The ratio of the tip clearance to the chord length is 1%. Both the width and the height of the squealer are 2mm.

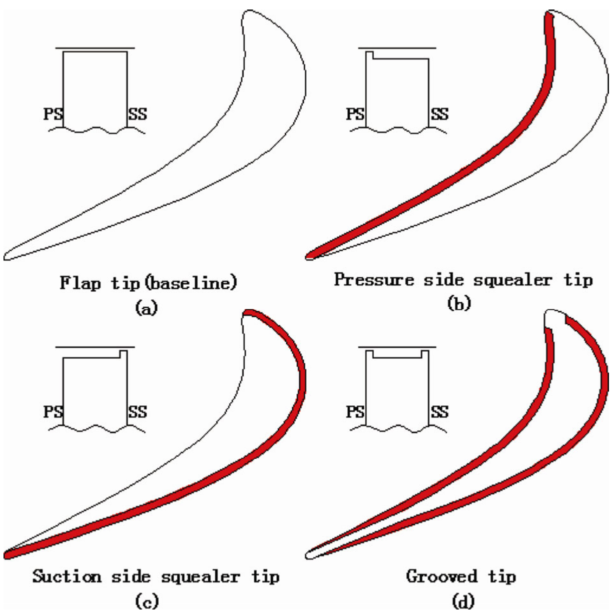


Fig. 5 Diagram of different tip geometries

The inlet free-stream velocity is kept at 10m/s and the Reynolds number based on the exit velocity and the chord length is 1.7×10^5. The incidence angle is maintained at 0 deg.

Fig.6 shows the distributions of static pressure coefficient on the tip end wall. As can be seen from Fig.6, for the flat tip configuration, there is a high pressure region near the leading edge because of the stagnation of the flow, and a low pressure region near the outlet as a result of contraction of the linear turbine passage. There exists large static pressure difference between the pressure side and the suction side from 20% to 80% of the axial chord. Due to the presence of the pressure difference, there exists a leakage flow at this region. A low pressure region is formed on the blade tip because of the acceleration of the leakage flow in the tip gap. The relative low pressure region on the suction side is the trajectory of the leakage vortex. There exists great pressure gradient at the pressure side for the flat tip, which means strong leakage flow.

The pressure side squealer tip being compared with the flat tip, the whole low pressure region on the position of the blade tip moves forward to the leading edge, and

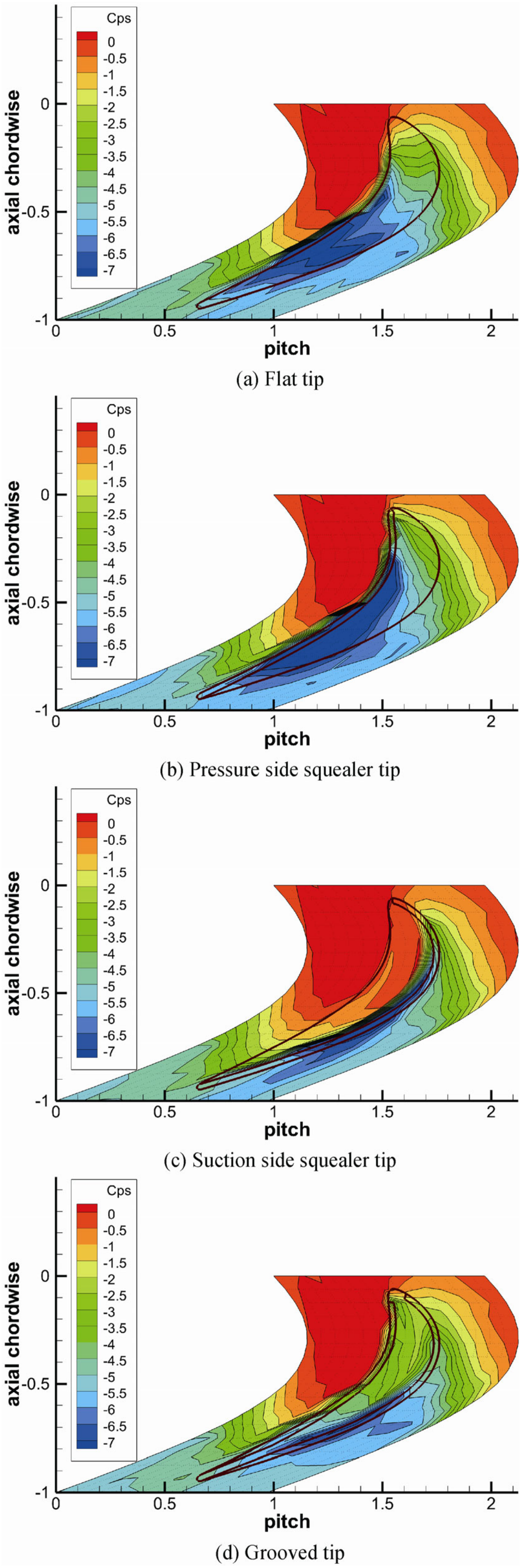


Fig. 6 Contours of static pressure coefficient, Cps

so does the leakage flow. As a result the mixing region of the pressure side squealer tip is larger than that of the flap tip region at the same traverse plane. The static pressure near suction corner is higher than that of the flat tip, which is due to the smaller velocity of the leakage flow. As a consequence, the core of the leakage vortex moves closer to the suction side.

For the suction side squealer tip, the low pressure range in the direction of the axial chord is smaller than that of the flat tip. The starting point of the occurence of the leakage flow is advanced. The static pressure near suction corner is lower than that of the flat tip, which means the velocity of the leakage flow is greater and makes the core of the leakage vortex move farther away from the suction side.

For the grooved tip, the range of the low pressure region is smaller and the static pressure is lower than that of the flat tip. The pressure gradient from the pressure side to the suction side is greatly decreased for the grooved tip and the static pressure drops slowly across the blade tip. There is almost no low pressure region on the position of the blade tip which indicates the intensity of the leakage flow is weakened.

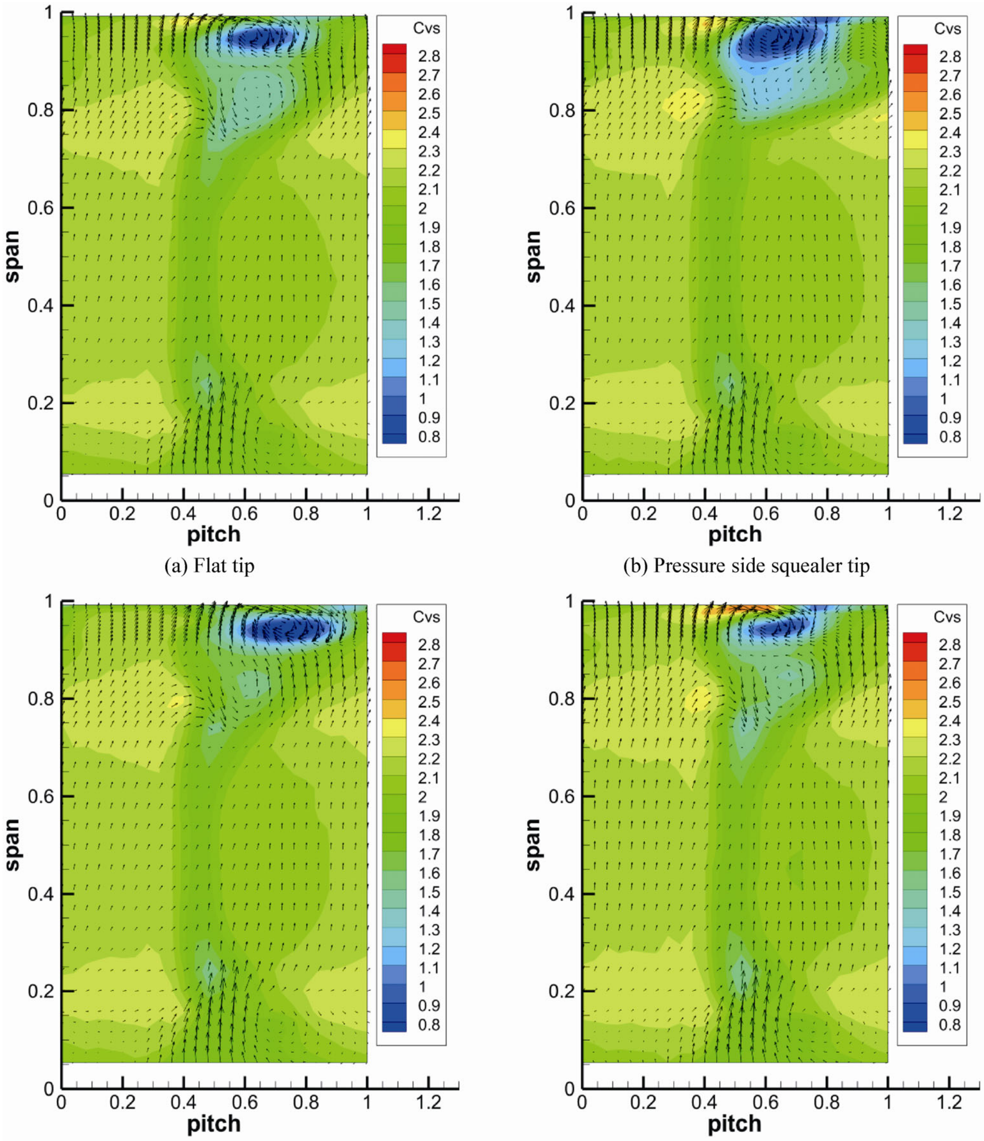
Fig.7 shows the distributions of the streamwise velocity coefficient and the secondary flow vectors at the 10% chord downstream from the cascade trailing edge. The secondary flow vectors are defined as the component of velocity projected to the plane perpendicular to the outlet camber line.

It can be seen that the high blockage region mainly exists in the wake region, the passage vortex region and the tip leakage flow region. The lowest streamwise velocity region which locates near the casing wall is the core of the clockwise leakage vortex. The upper counter-clockwise passage vortex which lies below the leakage vortex is weaker than the leakage vortex.

For the pressure side squealer tip, due to the lower momentum of the leakage flow, the core of the leakage vortex moves closer to the suction side. The low streamwise velocity region of the leakage vortex is larger than that of the flat tip, so is the pitchwise range of the passage vortex. The tiny low streamwise velocity region on the top-right of the leakage vortex corresponds to the vortex rolled within the blade tip gap.

For the suction side squealer tip, relatively high momentum of the leakage flow makes the core of the leakage vortex move farther away from the suction side. The low streamwise velocity region of the leakage vortex is much wider than that of the flat tip.

For the grooved tip, the low streamwise velocity region is much smaller due to the weaker leakage flow. The tiny low streamwise velocity region on the top-right of the leakage vortex corresponds to the vortex rolled within the channel of the blade tip. Hence the grooved tip can effectively improve the flow capacity of the passage and provide positive benefit compared with the flat tip.



(a) Flat tip (b) Pressure side squealer tip

(c) Suction side squealer tip (d) Grooved tip

Fig. 7 Secondary flow vectors and contours of streamwise velocity coefficient

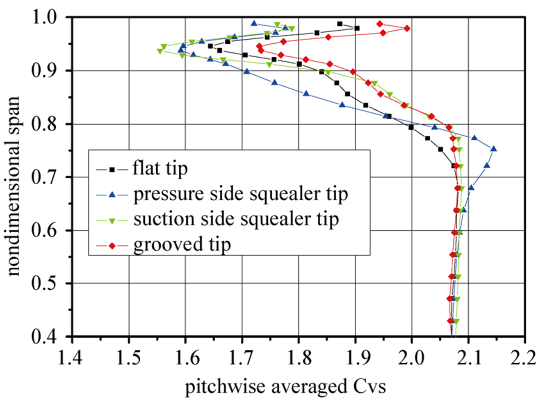


Fig. 8 Radial distributions of pitchwise area-averaged streamwise velocity coefficient

Fig.8 shows radial distributions of pitchwise area-averaged streamwise velocity coefficient. For the suction side squealer tip, the pitchwise averaged Cvs is higher than that of the flat tip from 70% to 90% span, and is lower above 90% span. For the grooved tip, the pitchwise averaged Cvs is higher than that of the flat tip from above 70% span, and hence the flow capacity of the passage is larger than that of the baseline.

Fig.9 shows the distributions of the total pressure loss coefficient. The distributions of total pressure loss coefficient is similar with that of the streamwise velocity coefficient. High loss region is in correspondence with the region of low streamwise velocity. Compared with the flat tip, the high loss region at the tip corner is larger for the pressure side squealer tip and wider for the suction

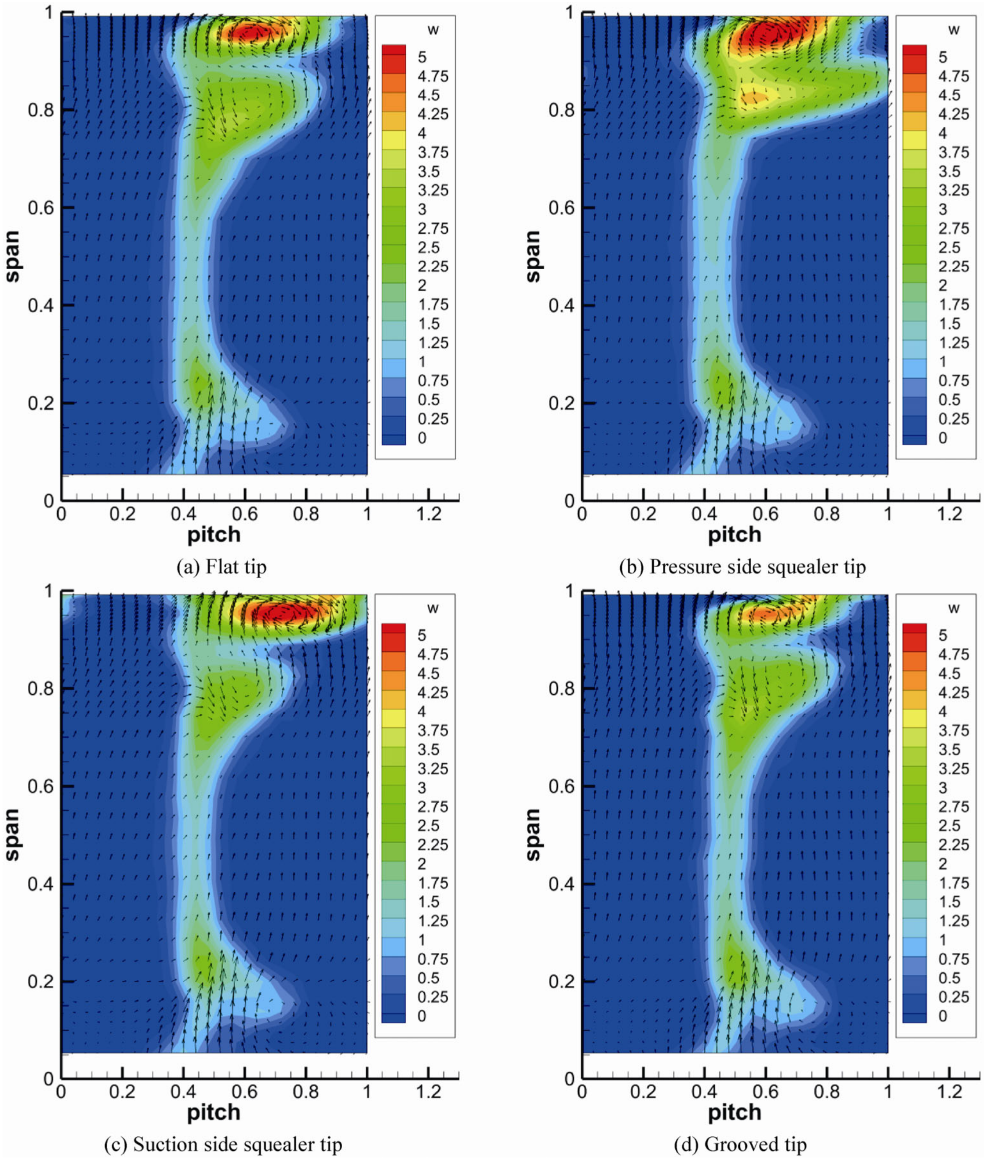


Fig. 9 Secondary flow vectors and contours of total pressure loss coefficient

side squealer tip. However, for the grooved tip, the total pressure loss region at the tip region is much smaller due to the weaker leakage flow.

Fig.10 shows radial distributions of pitchwise mass-averaged total pressure loss coefficient. The relative relationship of the pitchwise mass-averaged total pressure between these tip geometries is opposite with that of streamwise velocity coefficient. For the grooved tip, the pitchwise averaged loss is lower than that of the flat tip above 70% span.

Fig.11 shows radial distributions of pitchwise mass-averaged flow angle at the outlet of the turbine cascade. When the flow angle is 0 deg, it means the flow direction is perpendicular to the measurement plane.

It shows that the flow angle of the pressure side squealer tip is closer to 0 degree from 65% to 75% span and is farther from 0 degree from 75% to 95% than that of the flat tip. The flow angle of the grooved tip is closer to 0 degree at 92% span than that of the flat tip. It indicates that the flow direction is closer to the direction of the chamber line and the streamwise velocity is greater than that of the flat tip. It is in coincidence with the distribution of the streamwise velocity.

The overall performance of the cascade is measured by performing the area-weighted average for the streamwise velocity coefficient and mass-weighted average for total pressure loss coefficient over the entire measurement plane.

Fig.12 shows the area-averaged streamwise velocity coefficient over the entire measurement plane at the exit of the turbine cascade. The overall streamwise velocity coefficient of the suction side squealer tip and the grooved tip

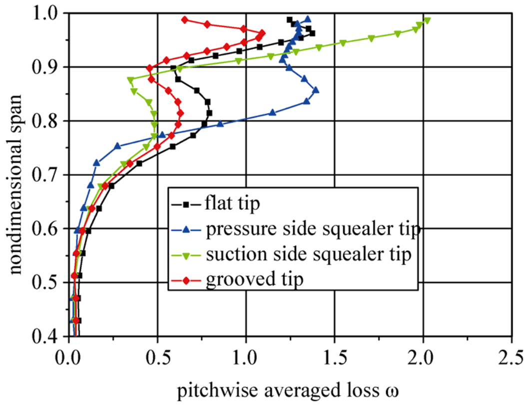


Fig. 10 Radial distributions of pitchwise mass-averaged total pressure loss coefficient

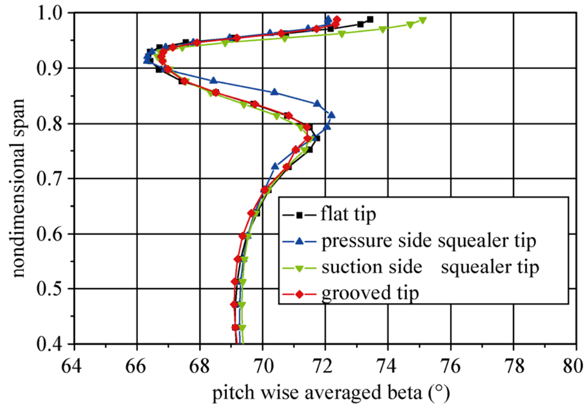


Fig. 11 Radial distributions of pitchwise mass-averaged flow angle

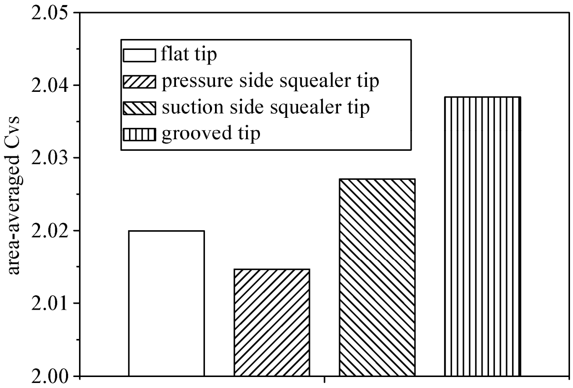


Fig. 12 Area-averaged Cvs over the entire measurement plane

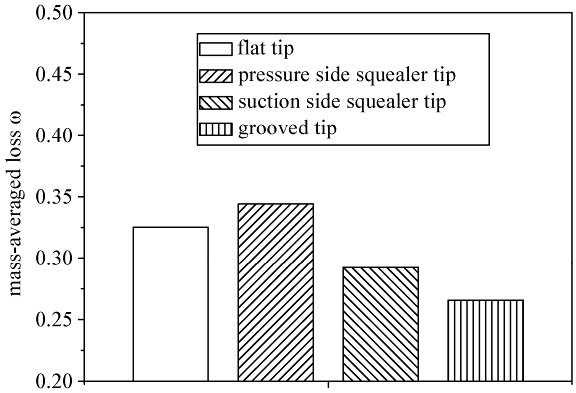


Fig. 13 Mass-averaged loss over the entire measurement plane

are greater than that of the flat tip .The leakage flow is weaker and the blockage region caused by the leakage flow becomes smaller, so the flow capacity of the cascade for the suction side squealer tip and the grooved tip is improved.

Fig.13 shows the mass-averaged total pressure loss coefficient over the entire measurement plane at the exit of the turbine cascade. The overall losses of the suction side squealer tip and the grooved tip are smaller than that of the flat tip, and the grooved tip performs the best.

Conclusion

The effects of the three kinds of tip geometries on the flow field of a turbine cascade passage are investigated. Several conclusions can be made.

(1) There exists large pressure gradient in the pressure side for the flat tip and the pressure side squealer tip, which means strong leakage flow. The pressure gradient from the pressure side to the suction side is greatly decreased for the grooved tip, and the resulting leakage flow is weaker.

(2) For the pressure side squealer tip, due to the smaller velocity of the leakage flow, the core of the leakage vortex moves closer to the suction side. For the suction side squealer tip, the velocity of the leakage flow is greater and makes the core of the leakage vortex move farther away from the suction side.

(3) The pressure side squealer has little advantages over the flat tip in improving the flow capacity and reducing the overall losses.

(4) The suction side squealer tip and grooved tip can effectively decrease the intensity of the tip leakage vortex, improve the flow capacity and reduce loss of the turbine cascade passage and the grooved tip performs the best.

Acknowledgement

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