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NUMERICAL INVESTIGATION ON TUIBINE SHROUD FILM COOLING HEAT TRANSFER PERFORMANCE OF TURBINE BLADE WITH GROOVE TIP

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Abstract

To reveal the influence of groove tip with cooling holes on turbine shroud film cooling, numerical simulation was carried out on turbine shroud. Studied the influence of shroud film cooling efficiency on thickness of tip groove wall, depth of groove, ρu of blade tip cooling air and turbine rotating speed. The result shows that, turbine speed has a significant effect on film cooling efficiency, the efficiency increases with the increase of turbine rotating speed. The tip cooling air is beneficial to the cooling of the second half of the shroud wall. The adiabatic wall temperature decreases with the increase of cooling air ρu, it is characterized by small flow and weak influence. The influence of groove wall thickness and groove depth on film cooling efficiency is weak correlation, they can be ignored in the design of turbine shroud cooling structure.

Keywords: turbine shroud; squealer tip; numerical analysis; film cooling efficiency.

1. Introduction

High pressure turbine shroud is an important structural component related to the reliability of aero-engine. It can keep the tip clearance of turbine blade and isolate high temperature gas. With the continuous improvement of the temperature in front of turbine, the working environment of the high pressure turbine shroud will be getting worse and worse. And at present, the cooling structure used in shroud can't guarantee that it won't be burned during operation. In the past, the domestic research on turbine shroud cooling focused on the impact cooling, film cooling and other cooling structures, but the influence factors of the external working environment were not well understood. The working environment of turbine shroud is the tip clearance of high pressure turbine rotor blades. At present, the research on shroud cooling, whether experimental or numerical methods, is carried out on the basis of flat tip. However, the groove tip which can better reduce the leakage loss of clearance is the most commonly used in engineering. At the same time, in order to ensure the life of the rotor blade tip, cooling holes are usually arranged on the blade tip to cool it down. Therefore, this paper focuses on the blade tip structure with cooling holes and its clearance flow, studies the influences on film cooling of turbine shroud.

Domestic and foreign scholars have carried out in-depth research on the tip and clearance flow of groove blade tip. According to Tamunobere[1], the high heat transfer region of turbine rotor blade tip moves to the leading edge of blade tip with the increase of blade rotating speed, which destroys the cooling effect of shroud film. Collins[2][3] found that the adiabatic wall temperature is greatly affected by the blade motion in the study of shroud film cooling. The tip leakage flow will impact and scrape off the boundary layer at the shroud wall, especially at the front edge of rotor blade tip. The leakage vortex will scrape the film away from the shroud wall, and the film cooling air will be involved in the passage vortex. Metzge[4] found that the ratio of groove depth to width and the ratio of tip clearance height to width have a great influence on the Nu of rotor blade wall. Newton[5] and Yang[6] have found that the film cooling efficiency of the blade tip is the highest when the tip cooling air holes are arranged on the attachment line. Zhou[7] considered that the film cooling at the tip of groove blade can obtain higher cooling efficiency than that at the tip of flat blade and reduce the heat load at the tip of groove blade. The leakage fluid at the top of the flat blade is separated and re-attached on the pressure side of the blade tip. The leakage flow is attached again, which makes the flow in the tip clearance more complicated. Ma[8] found that the interaction between tip leakage flow and tip cooling gas has a great influence on tip heat transfer. The research of Li Wei[9] shows that the protruding groove shoulder makes the air flow separation when passing through the blade tip pressure surface, forming a recirculation zone, hindering the leakage flow and reducing the leakage loss. The height of the groove shoulder has a great influence on the turbine efficiency, but the width of the shoulder has little influence on the flow field. Li Jun[10] used numerical method to study the unsteady film cooling characteristics of the relative motion of the rotor and stator with the arrangement of the middle arc at the tip of the groove blade. The research results of Yu Lei[11] show that, compared with flat tip blade, the groove structure of squealer tip blade will cause severe disturbance of leakage flow in the tip clearance. With the increase of groove height, the resistance of leakage flow through the clearance increases, but the groove height has an optimal value, and the tip heat transfer coefficient increases with the increase of groove height. Du Kun[12] analyzed the influence of groove depth and shoulder wall thickness on heat transfer characteristics of squealer blade tip. Zhou Zhihua[13] used the numerical simulation method to analyze the flow characteristics of the bottom surface of the squealer gap impacted by the leakage flow. Chen Ying[14] found that the clearance leakage vortices form separation vortices at the trailing edge of the blade, and the static pressure coefficient in this region rises sharply. The cooling holes in the shroud can make more cooling air spray to the blade tip surface, and then could improve the cooling efficiency of the blade tip surface. Du Xubo[15] studied the location of film holes, groove depth, rotating speed and tip leakage loss, concluded that tip leakage flow, wall heat transfer coefficient and film cooling efficiency are also affected by groove depth and rotating speed to a certain extent. Su Yanchen[16] found that step vortices, groove vortices and leakage vortices were formed at the tip of groove blade.

To sum up, domestic and foreign scholars have done a lot of researches on the groove tip blade, and have a deep understanding of the heat transfer and tip clearance flow characteristics of groove tip blade. However, most of these researches focus on the influence of tip clearance flow on turbine performance and blade tip heat transfer, lack of the understanding of influence of shroud film cooling. In this paper, numerical simulation method is used to study the influence of blade tip structure size, tip cooling hole's ρu and turbine rotating speed on shroud film cooling when rotor blade and shroud are moving relatively to each other, so as to guide the design of shroud cooling structure.

2. Methodology

2.1 Calculation model

The calculation model consists of a single channel high pressure turbine rotor blade and a fluid domain around a shroud. There are groove and cooling holes on the rotor blade tip (six cooling holes are arranged along the middle arc of the blade tip), and the diameter of the holes is 0.5mm. The film cooling holes of turbine shroud are inclined cylindrical holes with diameter of 0.6 mm and inclination angle of 30 degrees. The calculation model is shown in Figure 1. The fluid domain around the rotor blade is rotating domain, and the fluid domain around shroud and the film cooling holes is a static domain.

In the calculation model, the relative position between shroud wall and rotor blade is shown in Figure 2, and the position of the leading edge of blade tip corresponds to the second exhaust film holes on the shroud bottom wall. The fourth and fifth exhaust film holes are located in the middle of the shroud wall, and one half of the shroud bottom wall corresponds to one half of the blade tip (along the axial direction).

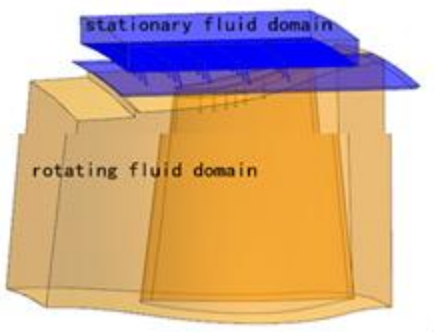


Figure 1 – Computing domain UG model.

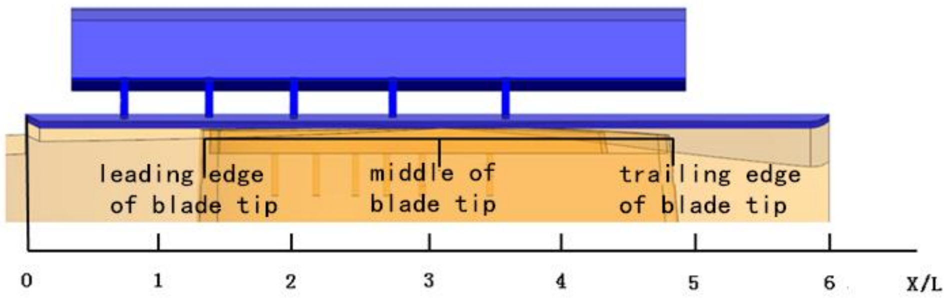


Figure 2 – Relative position of shroud and rotor blade.

2.2 Numerical Method

In this paper, ANSYS CFX18.1 is used to calculate the fluid dynamics. All the grids are tetrahedral grids. After the grid independence verification, the total number of grids is 120 million. The boundary layer is set on the wall of the fluid domain in contact with the solid. The SST k-ω turbulence model, which can be used to calculate the viscous bottom flow in the boundary layer with low Reynolds number correction, is adopted as the turbulence model, because the results of SST k-ω turbulence model are in better agreement with the experimental results in calculating the shroud film cooling efficiency, as shown in Figure 3.

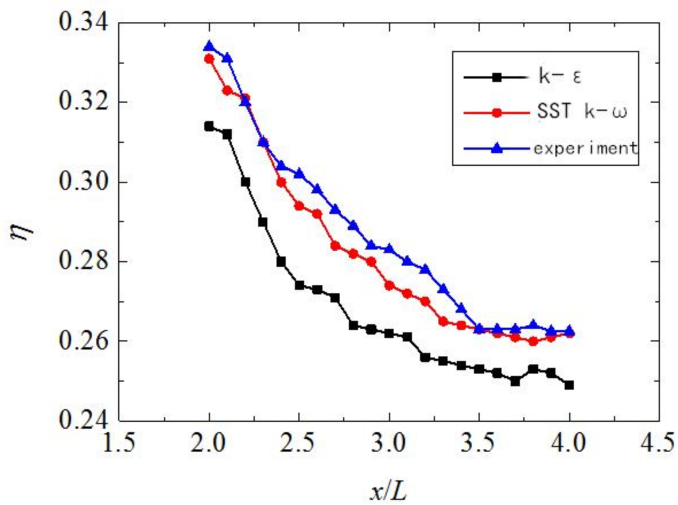


Figure 3 – Turbulence model validation.

2.3 Parameter Description

For the heat transfer in the clearance between the shroud and the turbine blade tip, the commonly used heat transfer criterion equation is as follows:

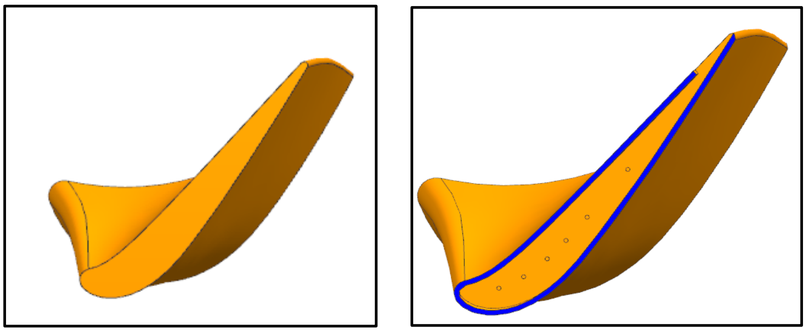
$$Nu = (A_1+A_2)\,Re^{0.8}Pr^{0.33} \quad (1)$$

Where, A_1 and A_2 is a function of the chord length of the turbine blade, the diameter of shroud bottom, and the distance from the tip of the turbine blade to the axis of the turbine. Rotational Reynolds (Re)is a function of rotor speed and tip clearance height. From the formula, it can be concluded that there are four characteristic dimensions that affect the Nu of heat transfer: the chord length of high pressure turbine blade, the diameter of shroud bottom, the distance from the tip of turbine rotor to turbine axis and the height of tip clearance. However, the formula is obtained under the condition of flat blade tip. The flat blade tip is quite different from the groove tip with cooling holes, which is widely used at present. Some structural dimension parameters are added to the groove tip, such as groove shoulder thickness and groove depth. These two parameters will affect r_2 and s. Tip clearance is one of the important characteristic dimensions that affect Nu and Re. Therefore, it is necessary to study the tip clearance height and the structure size parameters of the groove tip, and reveal their influence mechanism on shroud film cooling.

3. Result and Discussion

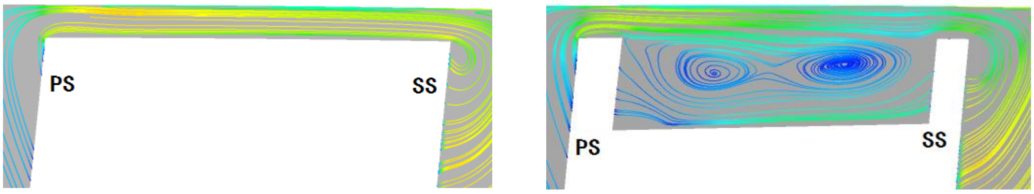
3.1 Compared with Flat Tip

Firstly, analyzed the distribution of shroud film cooling efficiency under flat tip and groove tip with cooling holes, and compared their differences. The blade tip diagram is shown in Figure 4.



Flat tip Groove tip with cooling holes

Figure 4 – Cross Section of Facility.



Flat tip Groove tip with cooling holes

Figure 5 – Streamline of a section in the tip clearance.

By comparing the flow lines of a section in the clearance under the two kinds of tip structures, it can be found that compared with the flat tip, the groove tip with cooling holes will form vortices in the tip groove, and after flowing out of the groove, it will converge with the clearance flow above and form a larger leakage vortex at the trailing edge of the suction surface.

Comparing the adiabatic film cooling efficiency of shroud bottom wall of the two kinds of tip structures under two typical working conditions, the results are shown in Figure 5 and Figure 6. Case 1 is the maximum heat load condition and case 2 is the minimum cooling air flow condition. It can be found that the film cooling efficiency of the shroud wall is significantly improved when there are cooling holes at the tip compared with the flat tip.

The flow path of the cooling air in the cooling hole on the blade tip is shown in Figure 7 and Figure 8. After the cooling air flows out of the cooling holes on the blade tip, it crosses the groove on the suction surface and gets involved in the leakage vortex on the suction surface at the trailing edge of the blade. In this model, the core region of the leakage vortex is located at the trailing edge of the tip suction surface, corresponding to the position between the fourth and fifth exhaust film holes of shroud bottom wall.

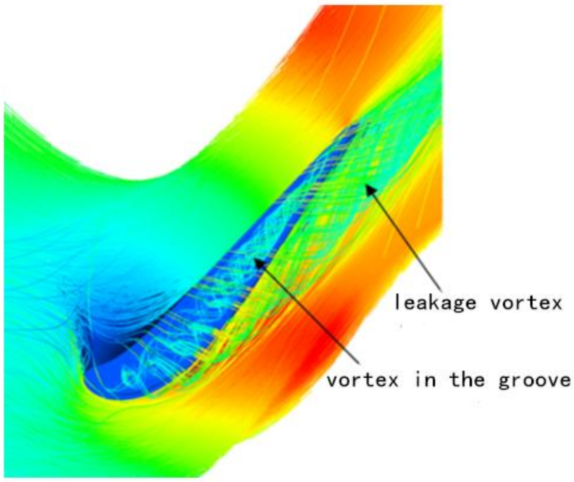


Figure 6 – Flow streaming of tip clearance flow in groove tip

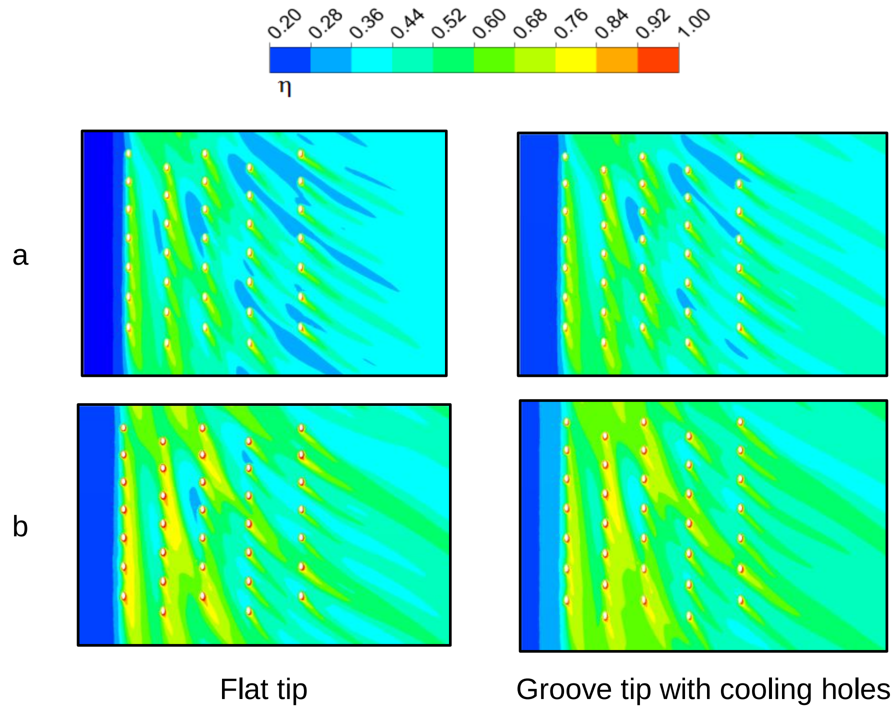


Figure 7 – Adiabatic film cooling efficiency cloud diagram of shroud
(a: case 1; b: case 2).

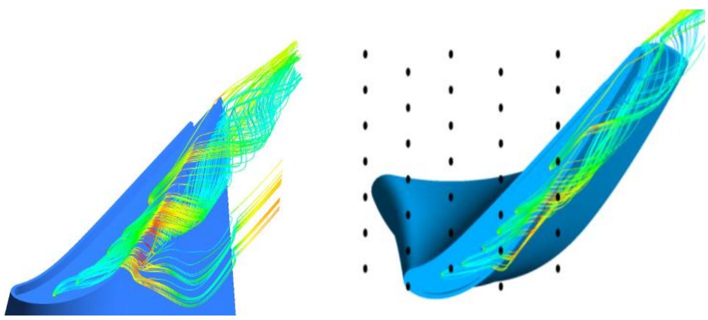


Figure 8 – Flow streaming of tip clearance flow in groove tip.

3.2 Influence of groove shoulder thickness

In this paper, based on the benchmark model, the influence of tip groove structure parameters and cooling air parameters on the shroud film cooling is studied. Firstly, the tip clearance height and groove depth are kept unchanged, and the thickness of groove shoulder is changed. See Table 1 for specific parameters.

Table 1 Parameter setting of calculation model(different th)

th	g	$\rho_2 u_2$	n	$\rho_1 u_1$	s
0.7%a					
1%a	2%a	500	15000	400	0.8%a&1.6%a
1.3%					
1.6%a					

Firstly, the influence of the change of the shoulder thickness on the shroud bottom wall static pressure is analyzed. Figure 9 and Figure 10 show the shroud bottom wall static pressure ratio curves corresponding to the four shoulder thickness under the clearance height of 0.8% a and 1.6%a, respectively. In the half area in front of the wall, the shroud wall static pressure corresponding to the shoulder thickness of 0.7%a is the lowest, and the average static pressure of 1.6%a is the highest. With the increase of the thickness of the shoulder, the clearance of the blade tip becomes smaller, the intensity of the vortex in the groove increases, and the effect on the clearance flow is enhanced, so a higher pressure gradient is needed to drive the flow. Therefore, with the increase of the groove thickness, the static pressure of the shroud gradually increases. At 0.8%a clearance height and 1.6%a clearance height, the same trend appears, but at small clearance height, the change of wall static pressure is smaller.

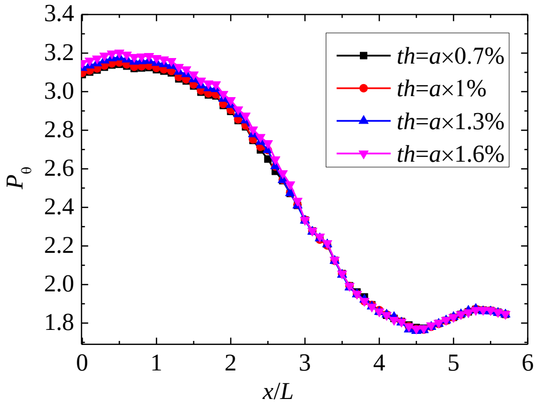


Figure 9 – Pressure ratio curve of shroud adiabatic wall(s=0.8%a).

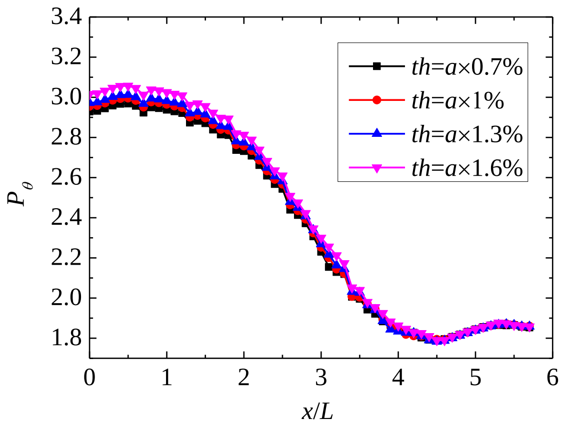


Figure 10 – Pressure ratio curve of shroud adiabatic wall(s=1.6%a).

Figure11 and Figure12 respectively show the distribution curve of the adiabatic film cooling efficiency of the shroud bottom wall with the groove shoulder thickness under two kinds of clearance heights. The maximum point in the curve corresponds to the position of the shroud film hole. It can be found that there is no difference in the adiabatic film cooling efficiency of different groove shoulder thickness in the half area in front of the shroud bottom wall, It is not enough to affect the cooling air flow and distribution of the shroud film holes'. In the second half of the shroud bottom wall, the cooling efficiency of the shroud with shoulder thickness of 1.6%a is the highest, and that with shoulder thickness of 0.7%a is the lowest. The tip cooling air mainly affects the middle and trailing edge of the blade tip suction surface, which is also the corresponding area of the last half of the shroud wall. With the increase of the groove shoulder thickness, the blade tip space decreases, the influence range of the tip cooling air increases, and the cooling effect of the shroud bottom wall increases, so the shroud bottom wall temperature decreases, The cooling efficiency increases. The influence of the shoulder thickness of the groove on the film cooling efficiency of the shroud is regular, but the influence is very weak. In the case of small tip clearance height, the difference caused by the groove shoulder thickness on the film cooling efficiency of the shroud bottom wall can be ignored.

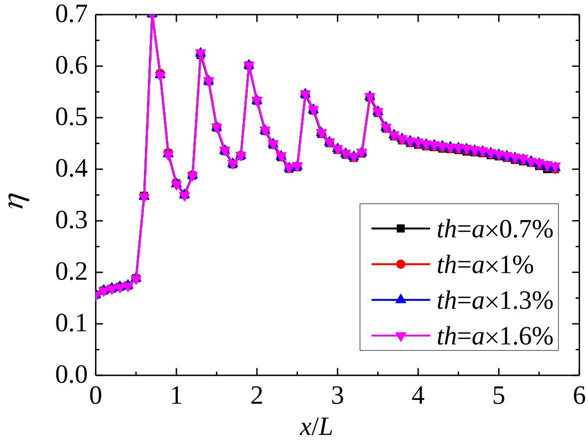


Figure 11 – Film cooling efficiency curve of shroud adiabatic wall(s=0.8%a).

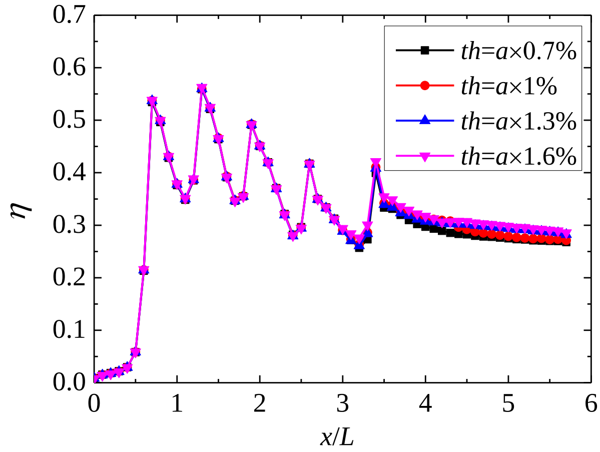


Figure 12 – Film cooling efficiency curve of shroud adiabatic wall(s=1.6%a).

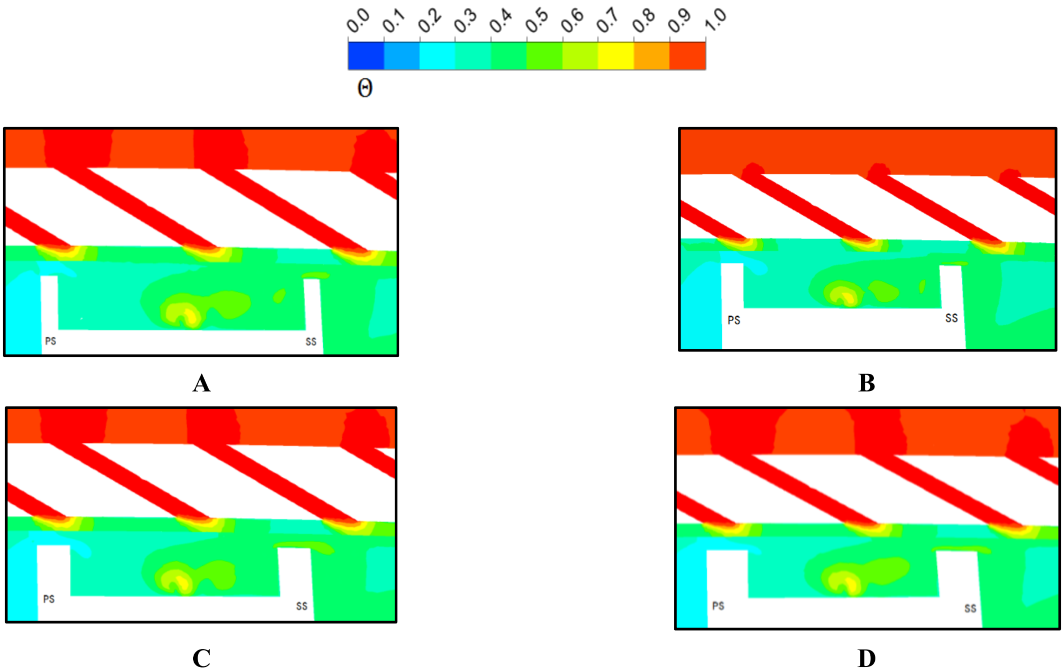


Figure 13 – Dimensionless temperature nephogram of a section in the tip clearance s=1.6%a (A: th=0.7%a, B:th=1%a, C:th=1.3%a, D:th=1.6%a).

3.3 Influence of groove depth

Ensure that the tip clearance height and the thickness of the groove shoulder are unchanged, and change the groove depth. See Table 2 for the specific parameters.

Table 2 Parameter setting of calculation model (different g)

th	g	$\rho_2 u_2$	n	$\rho_1 u_1$	s
	1%a				
	1.5%a				
1%a	2%a	500	15000	400	0.8%a&1.6%a
	3%a				
	3.5%a				

By analyzing the curves of the shroud wall static pressure ratio shown in Figure 14 and Figure 15, it can be concluded that the circumferential average static pressure of the wall is the lowest when the groove depth is 3.5%a, and the circumferential average static pressure of the wall is the highest when the groove depth is 1%a, because with the increase of the groove depth, the space in the tip increases and the vortex strength in the groove decreases, Therefore, the static pressure of the shroud wall presents a downward trend with the increase of the groove depth. The trend of the two kinds of tip clearance height is the same, although it presents regularity, but the pressure change is very small.

Figure 16 and Figure 17 show the adiabatic film cooling efficiency curve of the shroud wall. It can be concluded that when the groove depth increases from 1%a to 3.5%a, the adiabatic film cooling efficiency of the first half of the shroud bottom wall has no difference, while that of the second half of the shroud bottom wall is the lowest at 1% a and the highest at 3% a. the overall trend first increases and then decreases with the increase of the groove depth.

According to Figure 18, with the increase of the groove height, the intensity of vortex in the groove decreases, the disturbance effect of vortex on the shroud wall weakens, and the outflow of film holes on the shroud bottom wall can be better covered. Therefore, the adiabatic film cooling efficiency of the shroud bottom wall increases first, but with the further increase of the groove depth, the vortex in the groove almost has no effect on the shroud wall, At the same time, the driving pressure in the tip clearance decreases, the pressure in the clearance decreases, and the outflow of the shroud wall film holes will flow more into the tip clearance and can't better cover the shroud wall. At this time, the adiabatic film cooling efficiency decreases. Therefore, with the increase of groove depth, the shroud wall film cooling efficiency first increases and then decreases. However, it can also be observed from the curve that the difference between the values of the adiabatic film cooling efficiency is very small, which is more obvious at 0.8%a clearance height, so the influence of the groove depth on the adiabatic film cooling efficiency of the shroud is very small.

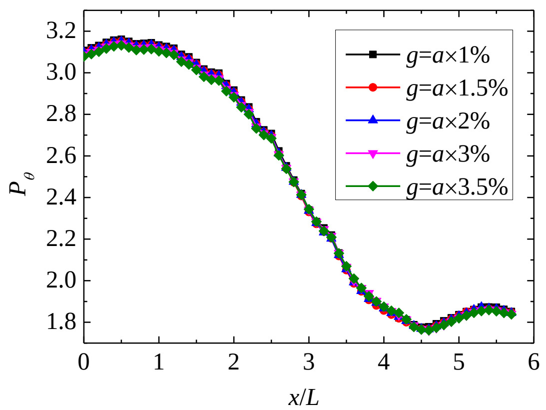


Figure 14 – Pressure ratio curve of shroud adiabatic wall(s=0.8%a).

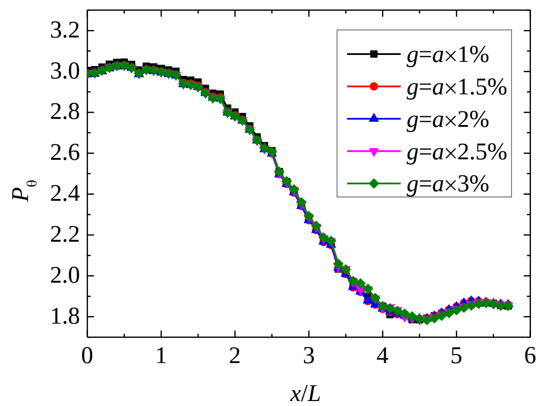


Figure 15 – Pressure ratio curve of shroud adiabatic wall(s=1.6%a).

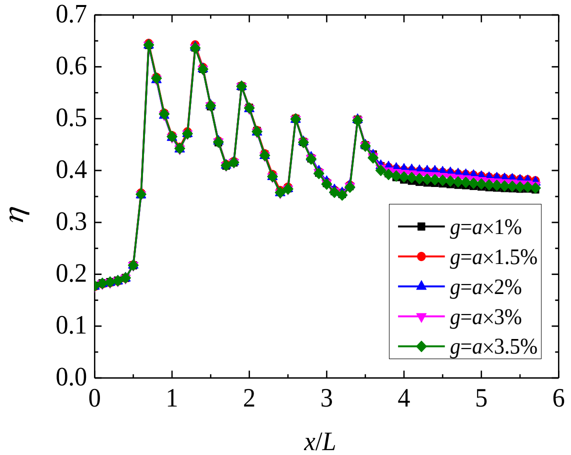


Figure 16 – Film cooling efficiency curve of

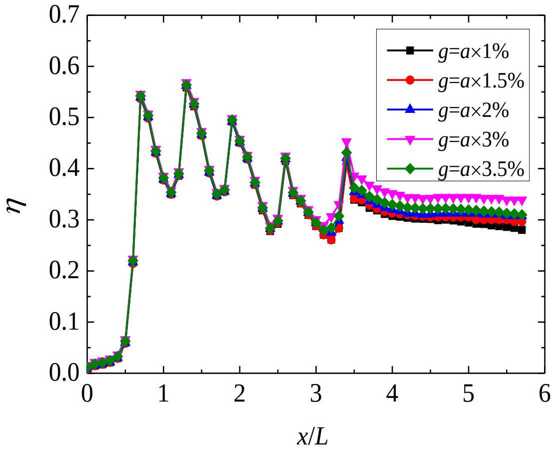


Figure 17 – Film cooling efficiency curve of

shroud adiabatic wall(s=0.8%a). shroud adiabatic wall(s=1.6%a).

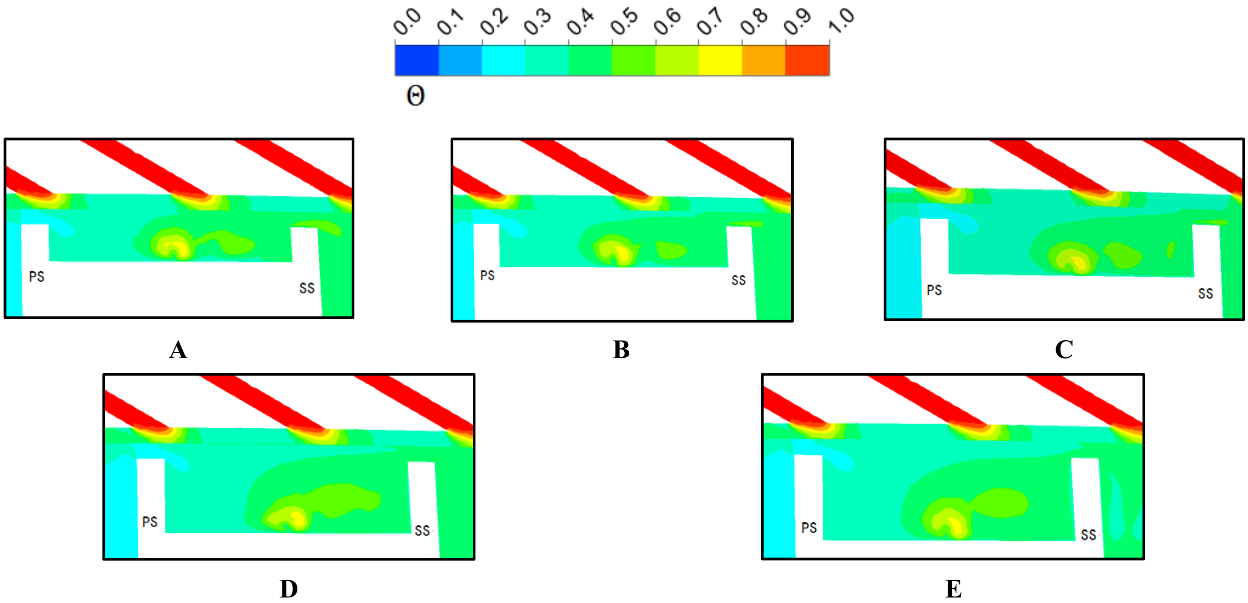


Figure 18 – Dimensionless temperature nephogram of a section in the tip clearance s=1.6%a (A: g=1%a,B:g=1.5%a, C:g=2%a, D:g=3%a, E:g=3.5%a).

3.4 Influence of tip cooling holes' ρu

On the premise of keeping the tip thickness、 the depth of the groove and the height of the clearance constant, the ρu of the cooling hole on the blade tip is analyzed. Analyzing the influence of tip cooling hole $\rho_2 u_2$ on film cooling of shroud wall. The cooling air $\rho_1 u_1$ of shroud film holes is fixed at 400, and the specific parameter settings are shown in Table 3.

Figure 19 shows the circumferential average static pressure ratio curve of the shroud bottom wall. The highest static pressure on the shroud bottom wall is at 333, When $\rho_2 u_2$ is 800, the static pressure of shroud wall is the lowest. Because when the $\rho_2 u_2$ is large, both of the flow rate and speed of cooling air at the blade tip is large, which leads to the increase of the flow rate in the tip clearance and the decrease of the static pressure on the wall. Therefore, the static pressure of the shroud wall will decrease with the increase of the cooling air $\rho_2 u_2$ of the blade tip cooling hole.

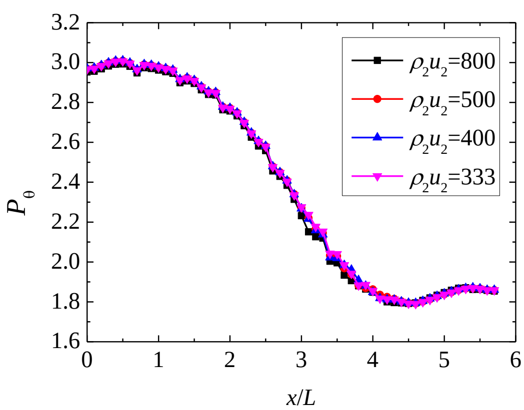


Figure 19 – Pressure ratio curve of adiabatic shroud wall

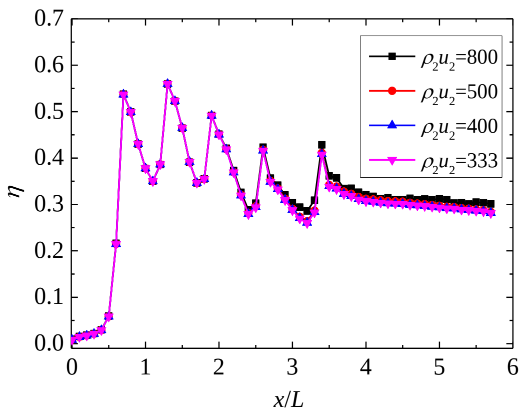


Figure 20 – Film cooling efficiency curve of adiabatic shroud wall

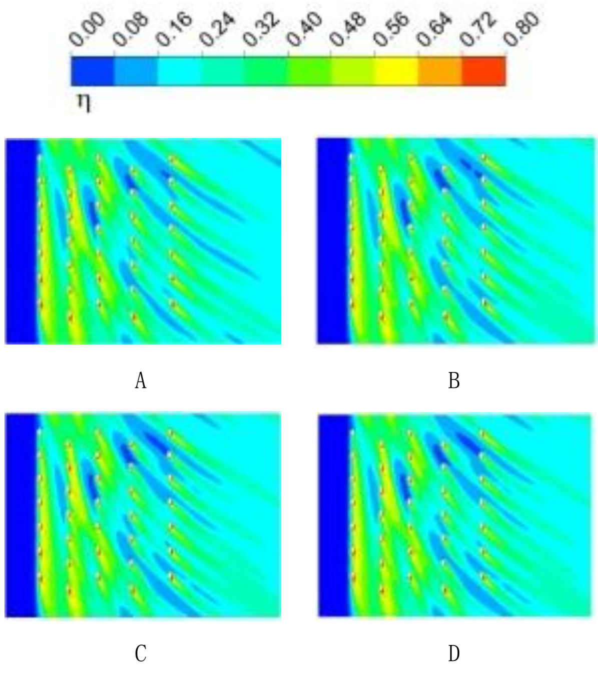


Figure 21 – Film cooling efficiency cloud chart of adiabatic shroud wall
(A:$\rho_2 u_2$=800, B:$\rho_2 u_2$=500, C:$\rho_2 u_2$=400, D:$\rho_2 u_2$=333).

From Figure 20 and Figure 21, we can get the influence law of the film cooling efficiency of the shroud bottom wall. The front half of the shroud wall is not affected by the change of the tip cooling hole $\rho_2 u_2$, and the adiabatic film cooling efficiency of the back half wall increases with the increase of the tip cooling hole $\rho_2 u_2$. The tip cooling air is helpful to the cooling of the back half wall of the shroud, but because of its small total cooling air flow and weak influence, it can't be considered in the design of the shroud cooling structure, and the design can be carried out under relatively worse external environment.

Table 3 Parameter setting of calculation model(different $\rho_2 u_2$)

th	g	$\rho_2 u_2$	n	$\rho_1 u_1$	s
1%a	2%a	800 500 400 333	15000	400	1.6%a

3.5 Effect of blade speed

Finally, under the condition that the thickness of the groove shoulder, the depth of the groove, the height of the tip clearance and the ρu of the cold air flow remain unchanged, the influence of the rotating speed on the shroud film cooling efficiency is analyzed. The parameter settings are shown in Table 4.

Table 4 Parameter setting of calculation model(different n)

th	g	$\rho_2 u_2$	n	$\rho_1 u_1$	s
1%a	2%a	500	3000 8000 15000	400	1.6%a

By analyzing Figure 22 and Figure 23, it can be concluded that the adiabatic wall temperature of the shroud decreases with the increase of the rotating speed, and the decrease is significant. The average adiabatic film cooling efficiency increases with the increase of the rotating speed, and the film coverage area increases, because with the increase of the rotating speed, the pressure difference between the tip pressure surface and the suction surface of the rotor decreases, and the clearance leakage flow rate decreases, which is also affected by the coriolis inertia force to a certain extent. The speed of the turbine has a great influence on the film cooling efficiency and the cold air coverage of the shroud, so the rotor rotation is an unsteady factor to be considered in the design of the shroud cooling structure.

In engineering applications, low engine speed is usually accompanied by low mainstream temperature, and high engine speed is also accompanied by high mainstream temperature. In the working conditions that need to play a cooling role to cool the shroud, the working conditions with high mainstream temperature and low speed are selected to design the cooling structure.

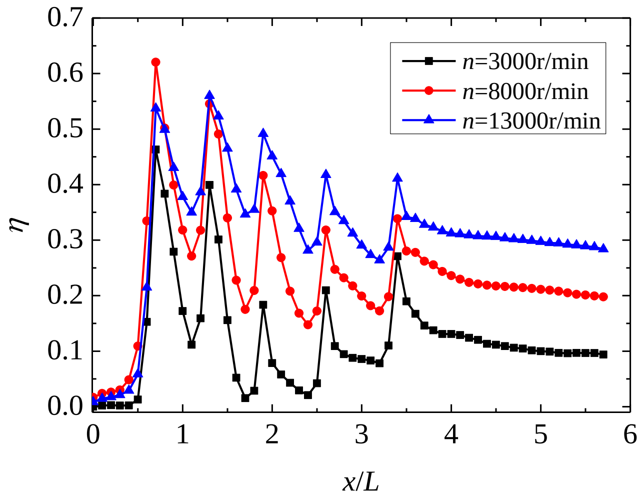


Figure 22 – Film cooling efficiency curve of shroud adiabatic wall

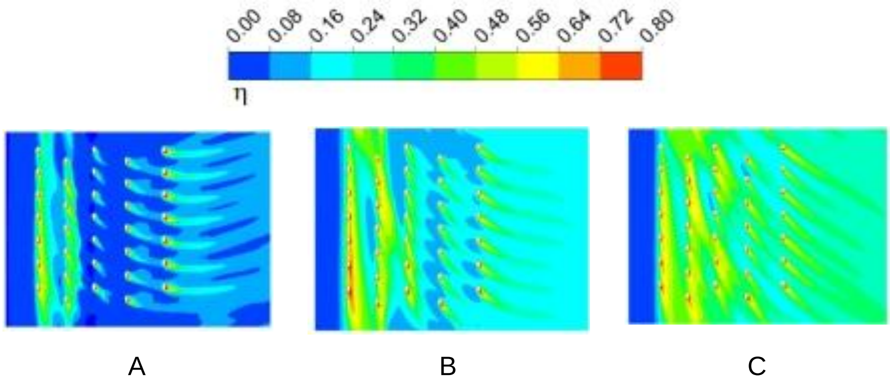


Figure 23 – Film cooling efficiency cloud chart of shroud adiabatic wall
(A: n=3000r/min, B:n=8000r/min, C:n=13000r/min)

4. Conclusions

The results show that there is a weak correlation between the thickness of the groove shoulder and the depth of the groove and the cooling efficiency of the adiabatic film on the shroud surface, and the influence of the groove structure on the cooling efficiency of the shroud can be ignored in the design of the cooling structure of the turbine shroud.

The tip cooling air flows out of the groove from the middle of the tip and joins with the clearance flow to get involved in the blade tip leakage vortex. Therefore, it is mainly conducive to the cooling of the back half wall of the shroud wall. The adiabatic wall temperature decreases with the increase of the $\rho_2 u_2$ of the cooling air, but the total cooling air flow is small, so the influence is small. Therefore, the tip cooling hole can't be considered in the design of the shroud cooling structure.

The results show that the speed has a significant effect on the cooling efficiency of the shroud wall, and the cooling efficiency increases with the increase of the rotating speed, so does the coverage area of the cold air. In the engineering design, the state point with high temperature and low speed is selected to design the cooling structure.

5. Nomenclature

a	High pressure turbine rotor blade height	mm
l	High pressure turbine rotor blade chord	mm
s	Tip clearance height	mm
d_1	Radius of shroud bottom	mm
d_2	Rotor tip rotation radius	mm
th	Blade tip groove shoulder thickness	mm
g	Tip groove depth	mm
$\rho_1 u_1$	Product of cooling air density and flow rate of shroud film hole	kg/m^2ts
$\rho_2 u_2$	Product of cooling air density and flow rate of blade tip film hole	kg/m^2ts
n	Rotor blade rotation speed	r/min
T_g	Mainstream temperature	K
T_{aw}	Adiabatic wall temperature	K
T_c	Cooling air temperature	K
T_0	Local temperature	K
T_θ	Dimensionless temperature	
Θ	Dimensionless temperature, $\Theta=\frac{T-T_g}{T_c-T_g}$	
η	Film cooling efficiency, $\eta=\frac{T_g-T_{aw}}{T_g-T_c}$	
P_0	Local pressure	Pa
P	Wall static pressure	Pa
P_θ	Dimensionless pressure, $P_\theta=\frac{P}{P_0}$	

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7. Copyright Statement

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