NUMERICAL STUDY ON FILM COOLING AND CONVECTIVE HEAT TRANSFER CHARACTERISTICS IN THE CUTBACK REGION OF TURBINE BLADE TRAILING EDGE

by

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Gas turbine blade trailing edge is easy to burn out under the exposure of high--temperature gas due to its thin shape. The cooling of this area is an important task in gas turbine blade design. The structure design and analysis of trailing edge is critical because of the complexity of geometry, arrangement of cooling channels, design requirement of strength, and the working condition of high heat flux. In the present paper, a 3-D model of the trailing edge cooling channel is constructed and both structures with and without land are numerically investigated at different blowing ratio. The distributions of film cooling effectiveness and convective heat transfer coefficient on cutback and land surface are analyzed, respectively. According to the results, it is obtained that the distributions of film cooling effectiveness and convective heat transfer coefficient both show the symmetrical characteristics as a result of the periodic structure of the trailing edge. The increase of blowing ratio significantly improves the film cooling effectiveness and convective heat transfer coefficient on the cutback surface, which is beneficial to the cooling of trailing edge. It is also found that the land structure is advantageous for enhancing the streamwise film cooling effectiveness of the trailing edge surface while the film cooling effectiveness on the land surface remains at a low level. Convective heat transfer coefficient exhibits a strong dependency with the blowing ratio, which suggests that film cooling effectiveness and convective heat transfer coefficient must be both considered and analyzed in the design of trailing edge cooling structure.

Key words: *gas turbine, blade, trailing edge, film cooling, heat transfer*

Introduction

With the development of gas turbine, the inlet temperature of blade improves continuously and the gas turbine blade withstanding high thermal load becomes critical component in the design of gas turbine. The thin blade trailing edge, which suffers sustained impingement of high-speed fluid and the leakage of high-temperature gas from the pressure side to the suction side, is prone to thermal damages. Therefore, the cooling of trailing edge is particularly difficult in gas turbine blade design.

In recent years, cooling of the turbine blade trailing edge has received extensive attention and many scholars carried out numerous researches on the cooling structure design of turbine blade trailing edge. Taslim *et al.* [1] studied the film cooling effectiveness of different shapes cooling grooves in a variety of blowing and density ratio, and found that lip thickness

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and groove height ratio are critical parameters of film cooling effectiveness in the trailing edge cutback region. Uzol *et al.* [2, 3] numerically investigated the aerodynamic loss characteristics of turbine blade with the application of trailing edge coolant injection technology. A variety of parameters, including the cutback length, the rib spanwise spacing, flow Reynolds number and the rib radial length were considered. It is found that the flow coefficient is largely independent of Reynolds number, therefore related experiments can be carried out at a relatively low Reynolds number. Holloway *et al.* [4, 5] conducted the experimental and numerical researches on the cooling of trailing edge grooves. It can be concluded that the gas reaches the surface faster with lower cooling effectiveness in measurements compared to numerical predictions. In other words, numerical analysis based on steady-state and Reynolds-averaged method presents better results than experimental measurements. Pu *et al.* [6, 7] performed a numerical study on the flow characteristics of actual cooling passages in low-pressure turbine blade, and they found that the flow characteristics depend on the inlet Reynolds number and the coolant jet outlet of blade tip. In addition, they also found that the fluctuations in the leading edge horseshoe vortex and the passage vortex increased and the frequency of horseshoe vortex in conversion process decreased with the increase of inlet flow turbulence of free stream. Yang *et al.* [8] numerically predicted the film cooling characteristics of typical trailing edge cutback using heat and mass match method and focused on the influence of some factors, including film cooling ratio and there is cutback or not, on the film cooling characteristics above trailing edge surface. It is summarized that the increasing of blowing ratio (BR) is beneficial for improving the streamwise film cooling effectiveness while decreasing the spanwise film cooling effectiveness. For most of researches about the trailing edge cooling of gas turbine, trailing edge film cooling characteristics are taken into main consideration. While the convective heat transfer performance inside the suction surface, which plays an important part in the cooling of trailing edge has got less attention. Horbach *et al.* [9] investigated the film cooling characteristics and convective heat transfer performance near the surface outside cutback. A variety of different finned structures arranged in the internal jet cooling channels were studied and it is found that the film cooling effectiveness and convective heat transfer coefficient outside the cutback both changes obviously.

In the present paper, the trailing edge geometry of gas turbine blade is modeled and the film cooling and heat transfer processes are investigated numerically. After the deep analysis of flow and heat transfer process near the trailing edge, the detailed relationships between cooling effect and cutback structure, film cooling BR are provided.

Objective

The cutback surface near the trailing edge of turbine blade is investigated in the present paper. When the high-temperature mainstream flows through the cutback surface, cooling gas ejected from internal cooling passages near the cutback produces the film covering in the cutback surface and convective heat transfer is existed in the suction surface at the same time. The reference trailing edge cutback modeled in the present paper is based on the test structure which is set-up by Yang *et al* [8]. Expanded geometry of cutback land, structure of smooth trailing edge cutback, and the main parameters are shown in fig. 1. As shown in fig. 1, smooth walls are applied both on the pressure surface and suction surface to imitate the real situation. The cut-

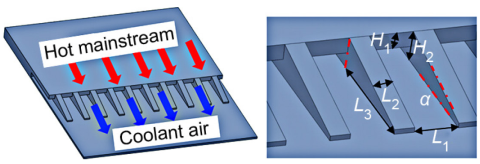

Figure 1. Cutback region of turbine blade trailing edge

back region with land, connecting the pressure side and suction side, which is connected to the adjacent internal cooling passage near the trailing edge is constructed. The cooling gas which is blown out along the cutback is mixed with the high-temperature mainstream impacting down from the pressure surface and produces the gas film and convective heat transfer effect in the corresponding suction side. The local part of blade trailing edge is cooled by the two effects substantially. The reference cooling channels in the trailing edge constructed in this chapter are based on four characteristic parameters: the land width $L_2 = 8$ mm, the width of cooling groove between cutbacks $L_1 = 17.4$ mm, the height of cutback $H_1 = 6.35$ mm, $H_2 = 12.7$ mm, the length of streamline in cutback $L_3 = 50.8$ mm. In the actual turbine blades, the outermost end of cutback is very close to the point of trailing edge. Therefore, the rectangular area within the cutback is the main object and the inclination angle of the cutback is $\alpha = 11.9°$.

Numerical method

For the numerical calculation in this chapter, the Reynolds-averaged Navier-Stokes method is used to solve the 3-D Navier-Stokes equations and the flow field and temperature field are obtained. The ANSYS Fluent is employed for numerical predictions. For the consideration of turbulence model, Martini *et al.* [10] carried out experimental and numerical investigations of film cooling characteristics in the trailing edge area. It is concluded that the realizable k-ε model performs a more accurate simulation for the phenomena of shear mixing and separation than other turbulence models and shows good correspondence with their own experimental data. Therefore, realizable k-ε model is selected as the turbulence model in present simulation.

The grids of cutback channels in the trailing edge arranged with different heat transfer structures are generated using the software ICEM CFD. In order to adapt the corresponding turbulence model and improve the accuracy of calculation, the heat transfer areas of walls where high-temperature mainstream and cooling jets flows flow past, are meshed with dense grids. The grid independence is preceded in cooling channels with Nusselt number of many monitoring points which is located on the cutback surface as the investigated variable. For cooling channels of trailing edge with and without land structure, the numbers of grids are 1.65 and 1.1 million, respectively. Figure 2 shows the local grids of some typical channels.

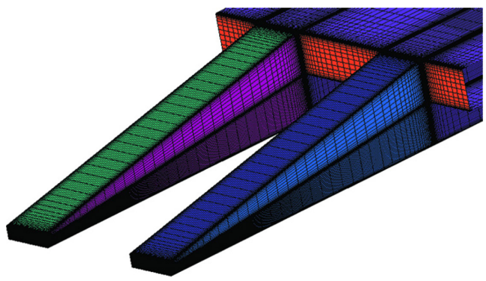

Figure 2. Numerical grid for cutback surface

For the numerical calculation the film cooling effectiveness and effectiveness heat transfer coefficient near cutbacks of the trailing edge should be considered together. Since the high-temperature mainstream and low-temperature cooling jets flow in the channels simultaneously, ideal gas which is compressible is set as the working fluid considering that some parameters of the gas, such as density, change with the temperature. The inlet velocity of cooling gas is determined by film cooling BR which ranges from 0.6 to 1 in the present investigation. The symmetry boundary conditions are applied on the side surface of channels in the spanwise because the channels of trailing edge are arranged periodically. For the calculation of film-cooling effectiveness and heat transfer coefficient, the cutback surfaces are adiabatic and constant heat flux, respectively.

Results and discussion

Typical flow structure of the trailing edge cutback

Firstly, the flow and heat transfer characteristics of a typical cutback on smooth trailing edge are analyzed. And the impacts of different film cooling BR and the land effect will be shown in detail. The 3-D flow streamlines near the cutback is drawn in fig. 3 with various BR and the flow streamlines are colored with the fluid temperature. Figures 3(a)-(c) refer to the geometries with land structure (BR from 0.6 to 1), while figures 3(d)-(f) refer to the geometries without land. It can be seen that the cooling film is formed on the cutback surface after cooling jets ejecting from the jet slot to cover the trailing edge. Then the cooling jets spread to the downstream and move to the land surface gradually in the form of streamwise vortex structure. And the mixed air covers the sidewall and the partial region of the upper part of the cutback. Downstream diffusion cooling jets are mixed with the high temperature mainstream gradually and a high temperature wall jet is formed which is covered in the region of the cutback. With the change of BR, the momentum of the coolant jet will be changed and the mixing process with high temperature mainstream will also be altered significantly. This will also significantly influence the film cooling effectiveness on the cutback surface. The entrainment mixing of the cooling jets and mainstream can also be seen in the figure. It can be found that the upward entrainment mixing of the cooling jets and mainstream along the side wall of the cutback. For larger BR, the momentum of coolant jets is higher which will wash through longer streamwise distance but the upward entrainment is not that intense. Land geometry is also important for the flow streamlines. It is seen that the land structure offers a geometrical restriction for the coolant jet which benefits the streamwise development of cooling film in that direction. Without land structure, the cooling air diffuses suddenly after exiting from the slot. The diffusion provides benefits for the spanwise development of cooling jet but it is hard to cover areas far from the cooling slot. The cooling film formation is also clear from the coloring of streamlines indicating fluid temperature.

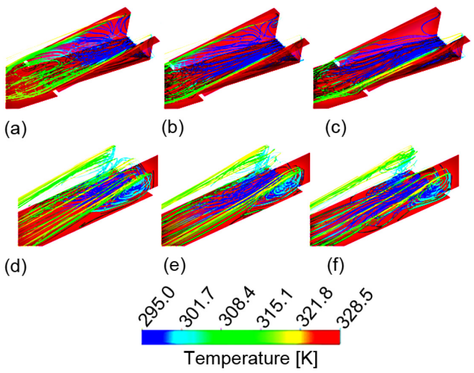

Figure 3. The 3-D flow streamlines and temperature coloring near the cutback region

Film cooling effectiveness and heat transfer coefficient distribution

Film cooling and convective heat transfer process are both important characteristics for the cooling of turbine blade trailing edge which are discussed in this section. The distribution of film cooling efficiency on the cutback surface with different BR is shown in fig. 4. For cutbacks with land geometry, the film cooling efficiency in the local area of the cooling jets outlet is close to 1 for all BR. In this case, the cooling air almost formed a perfect cooling film effect which covers the section regions of the cutback surface. Along the direction of flow, the cooling jets move downstream within the limitation of both sides of the wall surface of the cutback and gradually mixed with the high temperature mainstream. The film cooling effectiveness on the surface of the cutback is gradually decreasing until leaving the rear end of the cutback. The side wall of land structure and the cutback surface form the cooling channel of trailing edge ejection slot. The film cooling efficiency on the two side wall of land is high while it is still low on the upper surface of the land because that the surface contacts with high temperature mainstream directly, even though some of the cooling jets are entrained into the area above the land surface by the mainstream. Without the restrictions of land, the cooling jets are easily diffused towards the side generating better cooling efficiency on the original land region. But the cooling efficiency along the streamwise direction is not improved obviously. It should be noted that arrangement of land geometry is mainly based on the consideration of structural strength.

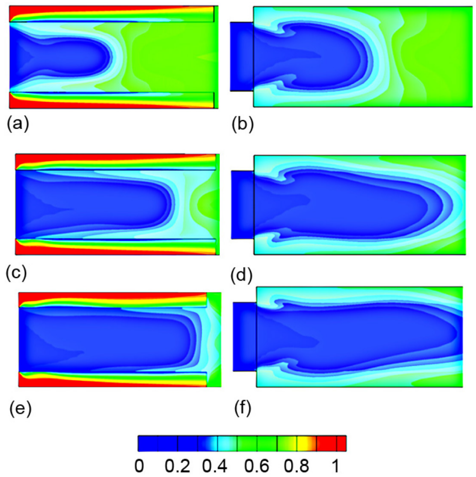

Figure 4. Adiabatic film cooling effectiveness distribution on cutback surface; (a) with land, *BR* = 0.6, (b) without land, *BR* = 0.6, (c) with land, *BR* = 0.8, (d) without land, *BR* = 0.8, (e) with land, *BR* = 1, (f) without land, *BR* = 1 *(for color image see journal web-site)*

By comparing the different BR, it can be found that the increase of BR has a significant improvement on film cooling efficiency of the cutback surface. When the momentum of cooling jets is larger, the energy of the cooling jets can push the high temperature mainstream flow to a further downstream region. The high film cooling efficiency area of the cutback surface will be expanding toward the downstream. But at the same time, for the cooling of the upper cutback surface, the energy of the downstream scour is larger when the momentum of cooling jets is larger. In this case, the high cooling BR will worsen the cooling effect of the upper cutback surface to a certain extent. Besides this, the improvements of film cooling effectiveness are not intense when the BR has increased to a certain level.

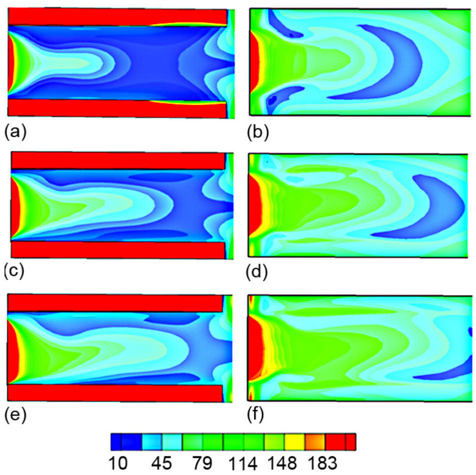

Figure 5. Convective heat transfer coefficient distribution on cutback surface; (a) with land, *BR* = 0.6, (b) without land, *BR* = 0.6, (c) with land, *BR* = 0.8, (d) without land, *BR* = 0.8, (e) with land, *BR* = 1, (f) without land, *BR* = 1 *(for color image see journal web-site)*

The convective heat transfer coefficient distribution can be seen in fig. 5. It is seen that higher BR still generate larger heat transfer coefficient due to larger mixed fluid velocity. The heat transfer on land surface is not considered in these calculations which could be ignored. The land effect is quite obvious. Without land geometry, the cooling jets and mainstream are mixed immediately and impinge on the cutback surface without the restriction of land structure. So the heat transfer coefficient is much higher for the cutback surface without land. With higher BR, the heat transfer coefficient is then increased but the effect is less influential when BR is higher than 1.

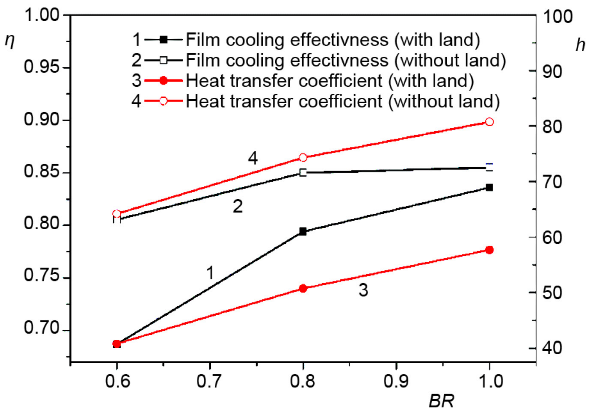

Figure 6. Overall thermal performance variation with Reynolds number

In order to quantitatively compare the film cooling and heat transfer effect of the cutback surface with each BR, the averaged film cooling effectiveness and heat transfer coefficient are evaluated on the cutback surface as indicated in fig. 6. As correspondent with the previous distribution, higher BR will generate larger film cooling effectiveness and heat transfer coefficient simultaneously. The effects of land geometry are significant for the average film cooling and heat transfer. With land structure which is based on the consideration of structural strength, the film cooling effectiveness and heat transfer coefficient are both lower than cutback without land. It indicates that land geometry has some negative effect on the cooling aspect which implies that both structural and cooling performance should be considered in the design the trailing edge.

Conclusions

The 3-D models of the trailing edge cooling channels are investigated with the consideration of film cooling and convective heat transfer by numerical methods. Flow characteristics, film cooling effectiveness, and heat transfer coefficient distribution are obtained. The following conclusions are obtained.

The mixing process of coolant jets and mainstream fluids are complicated on different BR. The upward entrainments are the key flow patterns near trailing edge cutback area. For film cooling process, the areas close to the cooling jet slot exhibit almost perfect film cooling effect and then cooling jets are diffused and mixed with high temperature mainstream generating lower film cooling effectiveness. Higher BR will generate larger overall film cooling efficiency. Heat transfer coefficient is also significant with the change of BR. Generally, with larger BR, the film cooling effectiveness and heat transfer coefficient are both larger. The land geometry also affects the cooling process. With land, the cooling jet is restricted to the cutback channel and it is hard to diffuse towards the two sides. Overall, land geometry provides negative effect on the film cooling effectiveness and heat transfer coefficient but it is designed based on structural considerations. The design of turbine blade trailing edge should be based on the consideration of film cooling, convective heat transfer and also structure.

Nomenclature

BR – film cooling blowing ratio, [–]
H_1 – lip thickness, [mm]
H_2 – land height, [mm]
h – heat transfer coefficient, [$Wm^{-2}K^{-1}$]
L_1 – length of single pass way, [mm]
L_2 – land width, [mm]
L_3 – land length, [mm]
T – temperature, [K]

Greek symbols

α – the inclination angle of the cutback, [°]
η – film cooling effectiveness, [–]
ρ – density, [km^{-3}]

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