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Investigation on the Effect of Blade Tip Winglet in a High Loading Transonic Rotor

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Abstract

Complicated interactions of leakage vortex, shock wave and boundary layer exist in tip region of high loading compressors, which result in larger aerodynamic losses in the passage. Even more serious is that the blockage induced by leakage vortex and flow separation in tip region of blade may aggravate the process of rotating stall in further. In order to attenuate the influence of leakage vortex and improve the stall margin of highly loaded compressor, the new rotors with tip winglet are investigated in this paper. The tip winglet is designed by extending the flat blade section with the maximum width of 0.5 times of local aerofoil thickness at blade tip. The results indicate the tip winglet has close relation to the trajectory and strength of leakage flow. As the angle between the vectors of leakage flow and main flow in tip region decreases due to existence of tip winglet, all the stall margin of three new rotors have improved, even with an over 9% increase in the new rotor with winglet around SS. The migration and accumulation of low-energy fluids in the corner near casing wall are affected significantly by the tip winglet. As a result, the winglet near PS of blade tip causes a larger accumulation of low-energy fluids in the corner near PS. It increases the driving pressure difference of leakage flow along chordwise direction which tends to increase the strength of leakage flow. In contrast, the winglet near SS of blade tip contributes to a little decrease of driving pressure difference near frontal part of new rotor, so the strength of leakage flow originated from leading edge has been attenuated to some extent in tip gap of the new rotor. As the leakage flow weakens in the new rotor with tip winglet around SS, its influence range in tip region is suppressed accordingly along streamwise. However, in consideration of the additional shearing of leakage flow with extended tip winglet, the losses in forward part of tip gap increase slightly in the new rotor with tip winglet around SS.

Nomenclature

P	Static pressure (kPa)
T	Static temperature (K)
$\vec{\xi}$	Vector of absolute vorticity
$\vec{W}$	Vector of relative velocity
Hn	Normalized helicity
ω	Angular velocity
W	Magnitude of relative velocity

Subscripts

PS	Pressure surface
SS	Suction surface

Introduction

Increasing the loading of compressor stage is one of the key methods to improve the thrust-weight ratio of aero-engine. However, high loading compressors are subjected to some problems, for example, larger aerodynamic losses, smaller stall margin and complicated flow phenomenon [1, 2]. Relative to the profits produced by loading increase, it’s wise to employ useful flow control for blades to improve the overall performances of highly loaded compressors, so various flow control methods have been explored to use in blade optimizations for this purpose [3]. In consideration of the influence of leakage flow on flow stability and stall margin of high loading compressor, the tip winglet is introduced in this paper to change the shape of blade tip for improving the complex flow in tip region of transonic rotor. In practice, the winglet was used in external flow initially to improve the lift-drag characteristic of wing and attenuate the flow separation near wing tips [4, 5]. Because of its great aerodynamic profits in wings, the tip winglet was then introduced into wind turbine blade to suppress the separated vortex near blade tip and reduce the aerodynamic losses [6, 7]. After the successful applications in external flow, the tip winglet has begun to use in turbine blade to improve the aerodynamic characteristics and the managements of thermal loads for unshrouded turbines [8~10]. Large aerodynamic losses and thermal loads are produced in tip region of high-speed turbines, and the leakage flow plays an important role on the flowfields in tip region. In other hand, the thickness of turbine blade is much larger, and complicated flow exists in tip clearance of rotors, such as separated bubble near pressure side over tips and local accelerated supersonic flow [11, 12]. Therefore, the shape of turbine blade tip has much closer relation to reduce losses induced by leakage flow and improve the flowfields in tip region of rotors [13]. Varied type of winglet has been investigated for optimizations of turbine blade tips. For example, tip platform extensions, winglet with cavity and winglet with shaped features [14]. In the studies of tip winglet on turbines, it’s found that the driving pressure difference, and charge coefficient of leakage flow seem to be changed due to the tip winglet, which attributes to decrease the strength of leakage flow and the losses induced by it in tip gap of rotor [10, 15]. To the winglet with tip platform extension in some studies of low speed rotor of cascade, the winglet around PS produces higher losses, while the winglet around SS produces fewer losses in comparison with the original one. Besides that, the winglet around PS reduces the discharge coefficient of tip leakage flow, and the winglet around PS reduces the pressure difference across the tip [16, 17]. To the tip winglet with cavity or gutter, most of the fluids entering the squealer cavity are from the frontal leading edge region, and it is ejected at various locations near suction side after migrating along the cavity. During this process, the Mach number of the flow changes from supersonic to subsonic quickly and some vortices appear in the cavity. Therefore, the new shape of blade tip reduces the flux of tip leakage flow significantly and the losses of leakage flow decrease accordingly [18, 19]. In addition, the use of tip winglet also can reduce the driving pressure difference of the tip leakage flow, which benefits to weaken the strength of leakage vortex. However, some opposite conclusions for the influence of tip winglet on characteristics of turbines have also been presented in other studies [20, 21].

According to the studies of tip winglet in external flow and axial turbines, whether it has beneficial influence on the flow characteristics of axial compressors is a new question needed to be discussed. Firstly, the leakage flow goes downstream in negative gradient and it’s easier to induce flow instability in tip region. Secondly, the thickness of blade tip is much smaller in compressor, so the effect of winglet on the complex flow in tip region is relatively limited even ignoring the stress change of blade. Although a few investigations of tip winglet on 2-D compressor cascade and low speed rotors have been performed until now, the detailed effects of winglet on flow characteristics and stall margin of high loading compressor rotor have not been illustrated clearly, and its application in compressors is also restricted inevitably [22]. Therefore, the following problems will be studied in this paper:

(1) The effects of tip winglet on overall performance and stall margin of highly loaded compressor rotor;

(2) How does tip winglet affect the trajectory and its evolution of leakage flow in tip region of transonic rotor?

(3) How does tip winglet impact the flow characteristic of transonic rotor near stall point?

(4) The optimum location to install the winglet around blade tip

Tip winglet design

The effects of tip winglet are studied on a high loading transonic rotor in this paper. The main parameters of rotor Baseline are shown in table 1.

Table 1 Main design parameters of rotor Baseline (0.3mm tip gap)

Pressure ratio	2.27		Different span		
Isentropic efficiency	91%		hub	Mid-span	tip
Stall margin	11%	Diffusion factor	0.3	0.42	0.56
Tip speed (m/s)	430	Loading coefficient	0.8	0.63	0.5
Rotational speed (rpm)	23500	Camber angle	49.3°	31.7°	8.5°

The tip winglet studied in this paper is designed melting together with the blade and installed around the suction side, pressure side and both sides of blade tip respectively. In practice, in order to explore the influence of tip winglet on characteristics of new rotors, the size of the winglet around each side of blade is the same, in winglet Specifically, the height of winglet is 3.5% of blade height with the absolute value of 1.75mm, and the width of winglet in blade tip is of 0.5 times of local blade section thickness along camber line from leading edge to trailing edge, and it extends from blade tip to 96.5% span smoothly with simple Bezier curves to eliminate the surface roughness in radial direction. Fig.1 shows the geometry of the tip winglet and the top view of the winglet installed around suction surface of the rotor.

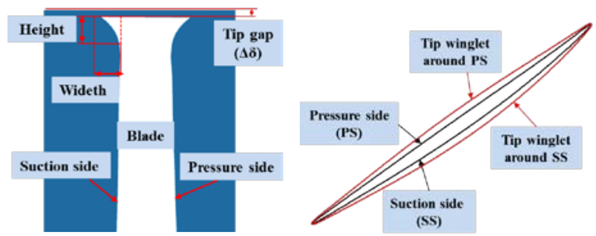


Fig.1 Structure of tip winglet

Numerical method

The steady numerical simulation has been performed in this paper. The RANS equations are discretized in space using cell centered control volume approach and in time using explicit multistage Runge-Kutta scheme for 3-D steady numerical calculations. The typical Spalart-Allmaras turbulent model is employed in numerical solver which is a one equation turbulence model with the better robustness and the lower additional CPU and memory usage. The calculation domain is divided into five different blocks with HOH topological structures in main flow and butterfly structured grids in tip gap to ensure higher gird quality. Fig.2 shows the grid topological structures in numerical simulations. In order to improve the reliability of numerical analysis, a 5×10-6m of first cell width near solid wall is chosen to ensure the y+<4.5. Total pressure, total temperature and absolute flow angle are given on the inlet condition; no-slip, no penetration and adiabatic wall boundary condition are given on blade surface, hub, shroud and other solid wall.

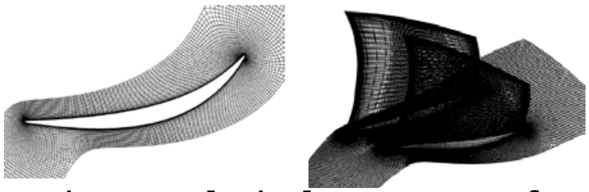


Fig.2 Topological structures of grids

In addition, the operation range of rotor in calculation is obtained through adjusting the back pressure of exit. The stalling point of rotor is taken to be the point at which the calculation diverges with a certain high back pressure (this is one of the most common ways to predict the stall boundary of compressor in numerical calculation). The stalling point obtained in this way is a best guess of when calculation failure occurs and it’s feasible to view it as an indication of stall inception.

Three levels of gird number, 45,000, 90,000 and 130,000, are used in calculations of rotor Baseline designed in this paper to evaluate the effects of grid number on calculation. The numerical results of three cases are shown in Fig.3. It seems the changes of grid number from 450,000 to 1,300,000 have less influence on the predicted results of spanwise parameter distributions in rotor. However, the gird number of 90,000 is chosen in present numerical simulation to predict the flow characteristics of rotors, in consideration of the cost in time and computing resources.

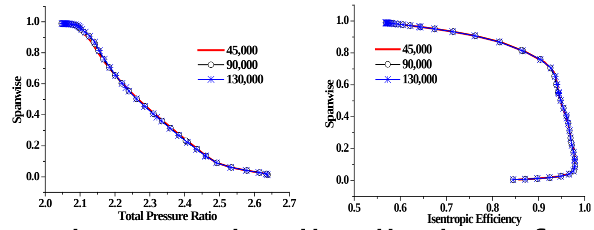


Fig.3 Spanwise distributions of pressure ratio and efficiency at exit of original rotor

The flowfields of NASA Rotor 37 are simulated to validate the numerical method used in this paper, and the comparisons of detailed experimental data and numerical results are described in Fig.4. Both the total pressure ratio and adiabatic efficiency in numerical method seem a little lower than the experimental results, but the maximum differences in two methods are no more than 4%. The contours of relative Mach number at 70% and 95% span are shown in Fig.6, it’s noted the detailed flowfields (including the tip clearance effects) have been captured in numerical calculation compared with experimental results. In conclusion, all the analyses above have well proved that the numerical method used in this paper has enough accuracy and satisfies the acquirement of calculation absolutely.

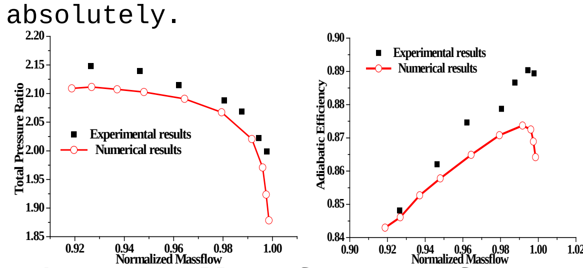
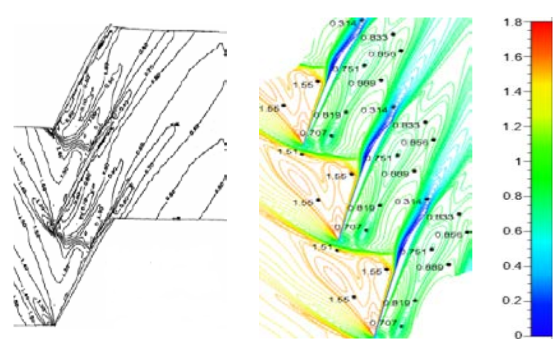


Fig.4 Overall performance of Rotor 37 at design condition

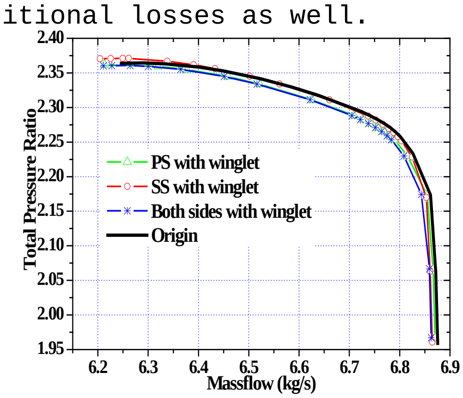


Experimental Numerical

Fig.5 Relative Mach number contours at 95% Span of Rotor 37 at 98% choke flow

Results analysis

The predicted overall performances of transonic rotors with different location of tip winglet at design rotational speed are shown in Fig.6. All the stall margins of new rotors with tip winglet around the PS、SS and both sides respectively have been improved obviously. Specifically, the new rotor with tip winglet around SS has an increase of over 9%, while the one with PS winglet presents a 3.3% increase. Moreover, the efficiency and total pressure ratio of new three rotors have decreased at peak efficiency point due to the appearance of tip winglet, which produces additional losses in tip region of blade. In comparison, the performance of the new rotor with tip winglet around SS seems much similar to original rotor with the smallest change of isentropic efficiency among the new three rotors (0.3% decrease). So it indicates from the overall performances of new rotors that the tip winglet benefits to improve the stall margin of transonic rotor significantly, but it produces new additional losses as well.



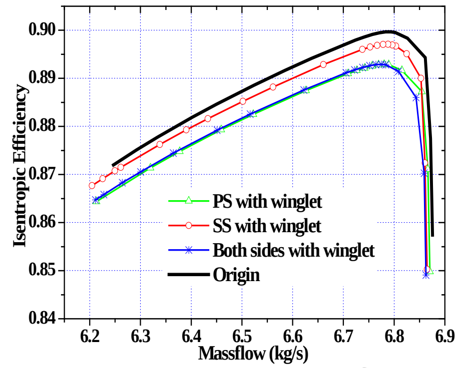


Fig.6 Characteristics of rotors with different location and the same size of tip winglet

Fig.7 shows the contours of entropy at mid-span of tip gap for peak efficiency point of rotors. When the leakage flow generates in tip gap because of the large difference of static pressure, it passes through the tip clearance with high relative velocity from PS to SS of blade, and shears with the stationary casing wall and rotational blade tip in this process. After getting out of the tip gap, the leakage flow interacts with main flow firstly and rolls up large-scale leakage vortex in passage. The leakage vortex with a slender core passes through the shock front near leading edge and induces a large low-velocity region close to PS of blade tip. After the interaction with shock, the shape of shock front in tip region has changed to be irregular and the leakage vortex decays gradually when it goes downstream in passage. In other hand, another part of leakage flow generates in gap from the latter part of blade tip. The intense of the leakage flow is relative weaker than the one originated from leading edge of rotor, it goes across the passage throughout the main flow and then enters the adjacent blade channel. Inevitably, another new low-velocity region forms in rearward part of passage during the process. It is clear in Fig.7 that large losses are produced in low-velocity region of the passage due to these irreversible processes. The entropy changes of new three rotors in

Fig.7 show that the corresponding losses in both two regions increase at peak efficiency point of three new rotors when the tip winglet is installed near blade tip, especially in the rotor with tip winglet around PS. However, the entropy distribution in tip gap of new rotor with tip winglet around SS is much similar to original rotor, which means the tip winglet may induce fewer losses when it is installed near SS of blade tip. In addition, the shears of leakage flow with casing and blade tip lead to a part of losses in tip region of new rotors as well.

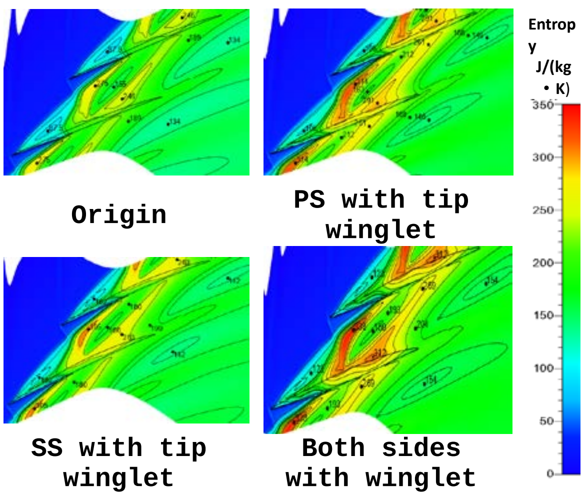


Fig.7 The contours of entropy at mid-span of tip gap at peak efficiency point of rotors

The interactions of leakage flow with shock wave and main flow appear to be intense in new three rotors at peak efficiency point, and the most leading cause is attributed to the pressure change near edge of blade surface which has close relation to the intensity of leakage flow and shock wave. The Fig.8 presents the static pressure distribution along blade surface edge for mid-span of tip gap in rotors. It indicates that the tip winglet around PS of rotor increases the pressure along pressure surface obviously while it has little influence on suction surface of blade tip. So the larger losses in tip region of rotor with tip winglet around PS relates to the stronger leakage flow produced by larger driving pressure difference along streamwise direction. In contrast, the tip winglet around SS of rotor only increases the static pressure of the rear part of suction surface of blade tip, but the increment is smaller than that of rotor with winglet around PS. In addition, the passage shock near leading edge of rotor with winglet around PS becomes a little stronger as well. As a result, both the stronger shock wave and the larger pressure difference near the rear part of blade tip produce slightly larger losses in tip region of rotor with winglet around SS. The pressure distribution of new rotor with tip winglet around both sides has all the change present in the former two new rotors.

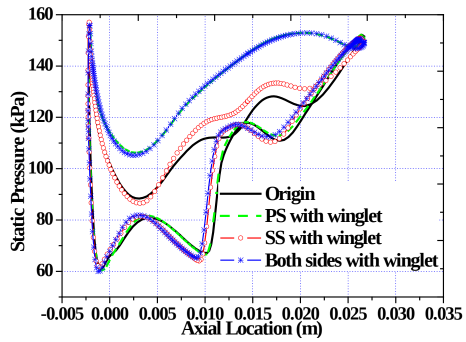
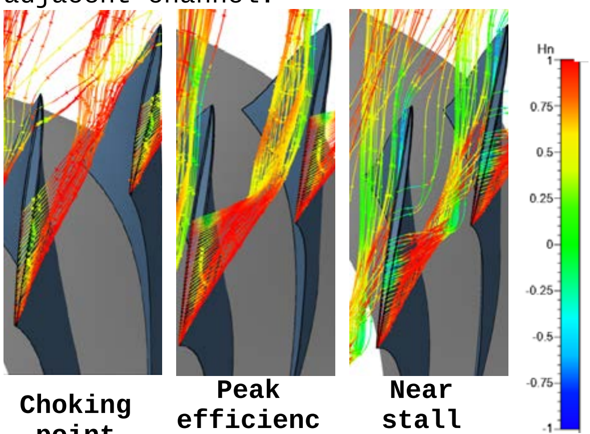


Fig8. The static pressure distributions along blade surface edge over tips at peak efficiency point of rotors

The tip winglet benefits to the stall margin of transonic rotor obviously which has shown in Fig.6, and it has close relation to the intense of leakage flow and blade loading in tip region. To explore the influence of tip winglet on flow characteristic of rotor near stall point, it's necessary to analyze the complicated flow in tip region of new rotors. Firstly, the normalized helicity is introduced to investigate the trajectory of leakage vortex in passage, which is defined as:

$$Hn = \frac{\vec{\xi} \cdot \vec{W}}{\left|\vec{\xi}\right| \cdot \left|\vec{W}\right|} \qquad (1)$$

Where $\vec{\xi}$ and $\vec{W}$ denote the vectors of absolute vorticity and relative velocity respectively. The normalized helicity Hn represents the cosine of the angle between the vectors of absolute vorticity and relative velocity, and it can be used to evaluate the nature of leakage vortex effectively. Since the flowfields in tip region of rotor is dominant by the component of absolute vorticity along the relative flow direction, the normalized helicity tends to be unity where the streamwise vortex is present. Fig.9 shows the distribution of Hn along the main relative flow in tip gap of the original rotor at different conditions. As the back pressure increases near exit of rotor, the blade loading improves accordingly and the driving pressure difference of leakage flow increases inevitably. So it can be seen that the strength of leakage flow increases obviously, and the concentrated vortex core of leakage vortex migrates from SS to PS of blade gradually when it goes downstream in the passage. At choking condition, the leakage flow is relative weaker, it seems to be pushed aside by main flow in tip region and the leakage flow almost can’t reach the pressure surface of blade. However, when the flow in rotor approaches stall point, the leakage flow becomes stronger and it collides with the pressure surface near leading edge of rotor after interacting with passage shock and main flow, even a part of leakage flow enters the adjacent channel of rotor. In addition, when the strength of leakage vortex is weak at choking condition, it goes downstream along the streamlines of relative flow in tip region and the value of Hn doesn’t change in this process. As the leakage flow become stronger due to larger driving pressure difference, the vortex core of leakage flow appears to be much closer to PS before it passes through the shock front. After the interaction with shock front and main flow, the leakage flow decays and the trajectory becomes much complicated. A part of decayed leakage flow goes downstream along main flow, while another part shears with the PS surface when it goes downstream, even enters the adjacent channel.

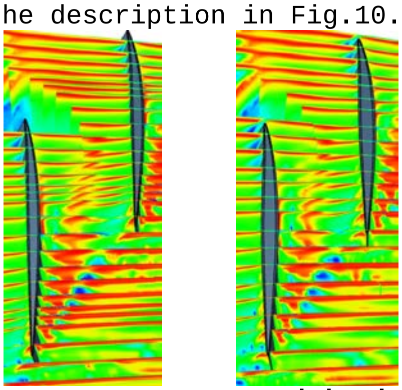


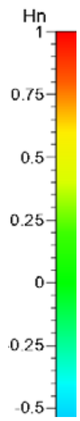
Choking point | **Peak efficiency point** | **Near stall point**

Fig.9 Distribution of Hn along streamlines of relative flow in tip region of rotor at different conditions

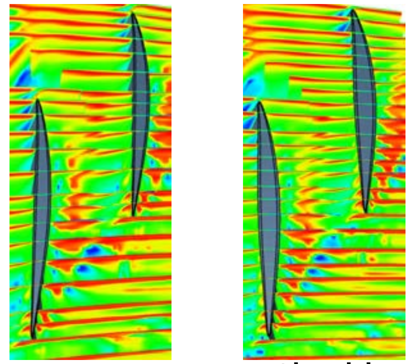
Fig.10 shows the distributions of Hn in tip gap near stall point of rotor with the same back pressure. Firstly, it can be seen in figure that the vortex cores of leakage vortex in new rotor is much closer to suction surface when it generates near leading edge of rotor. After the interaction of leakage vortex with shock front, the branched structure of decayed leakage flow presents in rotors as well. Differently, a part of leakage flow along main flow is still much closer to SS of blade in new rotors, and the location of the collision between another part of decayed leakage flow and PS has moved downstream compared with the original one, especially in the new rotor with tip winglet around the SS of blade. The changes of leakage flow in new rotors contribute to attenuate the blockage in tip region of rotor and postpone the spillage of main flow form leading edge of blade.

To confirm the flow phenomenon described in Fig.10, the trajectory of leakage flow in new rotor near stall point is present in Fig.11. Only the streamlines of leakage flow originated from the forward part of blade gap are drawn in tip region. With the same back pressure, the vortex core of leakage vortex is much closer to SS in new rotor when it is produced and goes downstream in passage. So it can be drawn from the change of trajectory for leakage flow that the tip winglet contributes to a reduction of angle between the vectors of leakage flow and main flow in tip region of new rotors. After the leakage vortex passes through the shock front, it decays obviously with the flow velocity decreasing rapidly and a typical branched leakage flow appears in passage. One part of branched leakage flow goes downstream directly and maintains a larger distance away from PS of blade in new rotor, especially in the one with tip winglet around SS. Meanwhile, the other part of leakage flow in new rotors collides with the pressure surface much more downstream in the passage of new rotors, which is consistent with the description in Fig.10.



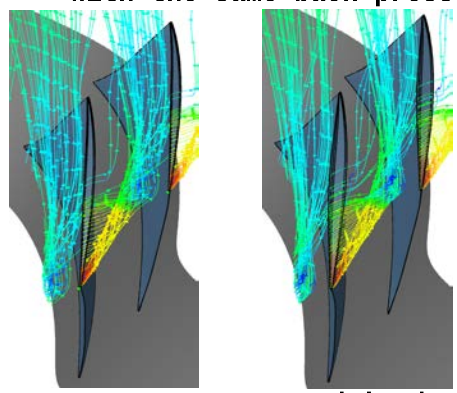


Origin **PS with tip winglet**

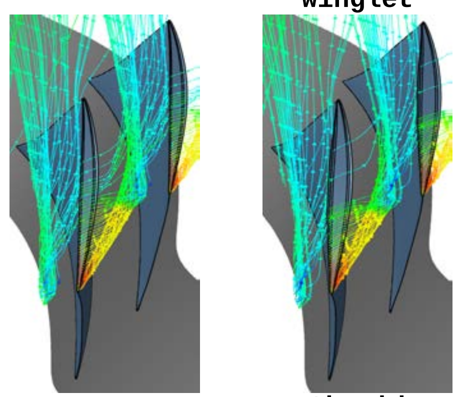


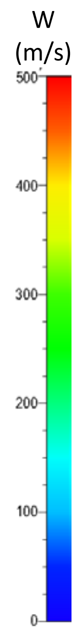
SS with tip winglet **Both sides with tip winglet**

Fig.10 The contours of Hn in tip region near stall point of rotor with the same back pressure



Origin **PS with tip winglet**





SS with tip winglet **Both sides with tip winglet**

Fig.11 Trajectory of leakage flow in tip region of rotors near stall point with the same back pressure

Fig.12 shows the contours of static pressure in tip gap of rotors near stall point with the same back pressure. According to the characteristics of vortical flow, the static pressure near vortex core is lower than surrounding, so the path of vortex core can be determined by static pressure trough for isoline. Therefore, the trajectory of leakage vortex core is present in tip gap from the distribution of pressure isolines, even the shearing surface between main flow and leakage vortex is displayed as well. The Fig.12 indicates that the leakage vortex cores in three new rotors are much closer to SS of blade near stall point, especially in the rotor with tip winglet around SS. It means the strength of leakage vortex tends to be a little weaker in rotors with tip winglet, and the leakage flow has been pushed away close to SS when it interacts with the dominated incoming flow. Besides that, the location of collision between leakage flow with PS move downstream in new rotor with tip winglet as well. In practice, the leakage flow changes to be the weakest when tip winglet is installed around SS of blade, and it is easier to be pushed aside by incoming flow, which benefits to suppress the region with large low-velocity and high-entropy flow.

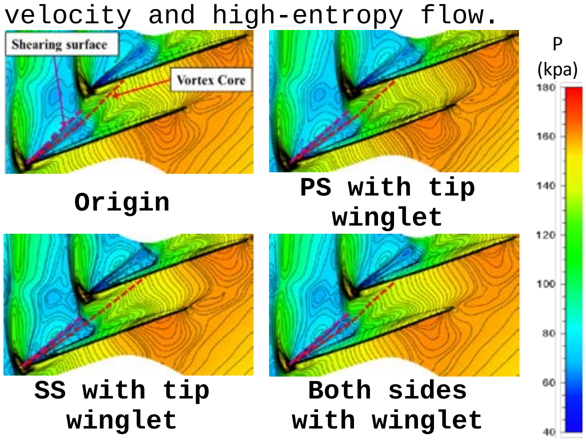


Fig.12 The contours of static pressure in mid-span of tip gap near stall point of rotor with the same back pressure

Fig.13 shows the contours of entropy at mid-span of tip gap near stall point of rotor with the same back pressure. The distribution of entropy in tip gap of new rotor with tip winglet around SS appears to be similar to that in original rotor, while the entropy changes increase obviously in tip gap of rotor when the tip winglet is installed near PS of blade. It's evident from the change of entropy in tip gap of rotor that with winglet around SS, the losses in tip clearance presents a little increase in the interaction of the forward part of leakage flow with shock wave and incoming flow near leading edge of rotor. However, almost no change of losses appears in the interaction of the rearward of leakage flow with main flow when the second part of leakage flow traverses the passage in tip region. In contrast, both the losses generated in the two interactions have increased evidently in tip gap of the new rotor with winglet around PS of blade.

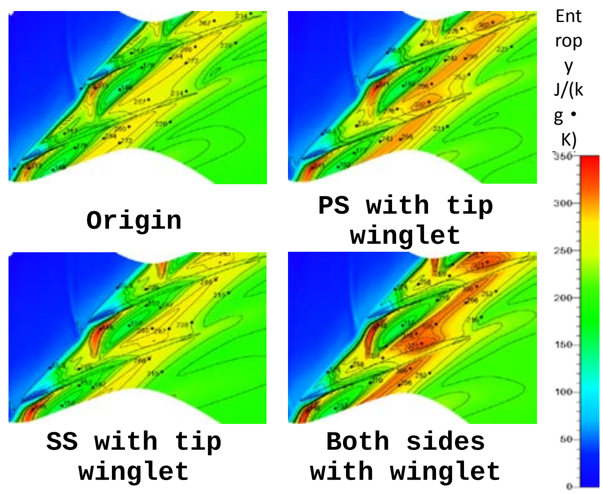


Fig.13 The contours of entropy at mid-span of tip gap near stall point of rotors with the same back pressure

To illustrate the reason for the change of losses in tip gap, Fig.14 shows the static pressure distributions along blade surface edge over tips near stall point of rotors. As evident in the pressure distributions in tip gap of the new rotor with tip winglet around SS, the driving pressure difference near leading edge has reduced slightly, while it increases a little in the latter part of clearance. In practice, the changes of pressure difference have close relation to the strength of leakage flow generated in tip gap. In other hand, it's also noted in Fig.14 that the strength of passage shock near leading edge presents a slight increase in tip gap of the new rotor due to the existence of winglet near SS. Coupled with the additional shearing of the leakage flow with rotational tip winglet, the losses appear to be a little increase in forward part of tip gap, but it seems similar to that of original rotor, which is shown in Fig.13. Differently, to the new rotor with tip winglet around PS, the driving pressure difference over blade tip increases greatly along the chordwise direction of the new rotor, and it can cause much stronger leakage flow in the whole tip gap. After interactions of the stronger leakage flow with the shock wave, main flow and solid walls surrounding it, the losses produced in two high-entropy regions of tip gap increase in the new rotor with winglet around PS compared with the original rotor.

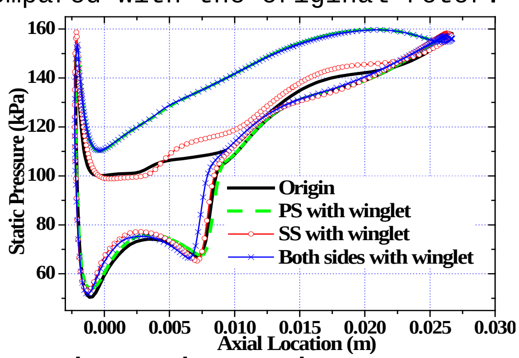
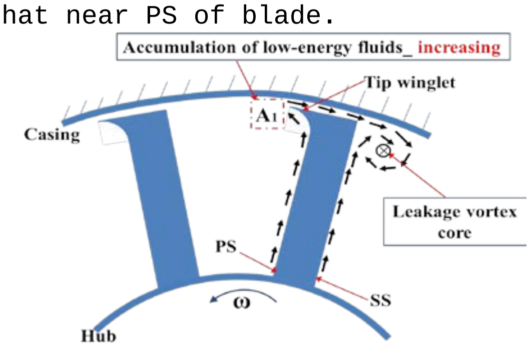
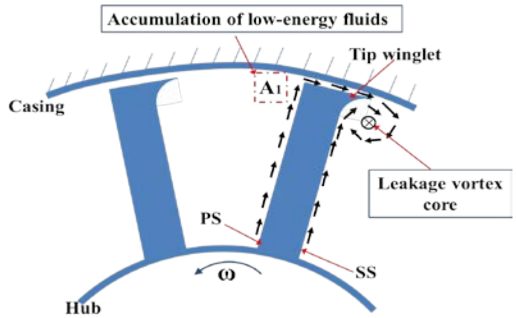


Fig.14 The static pressure distributions along blade surface edge over tips near stall point of rotors with the same back pressure

Fig.15 shows the migrations of low energy fluids near blade surface of new rotors with tip winglet. Driven by the centrifugal force of rotational rotor, the low-energy fluids in boundary layer move from hub to tip region along chordwise direction. For the new rotor with tip winglet around PS, much larger of the low-energy fluids accumulate near corner between PS and casing wall in tip region (labeled as A1) due to the restriction of the extended winglet near PS of blade tip. As a result, the local pressure at entrance of tip gap near PS increases greatly along chordwise direction of the new rotor with winglet around PS of blade, shown in Fig.14. Different from the former new rotor, the low-energy fluids in corner region of the new rotor with winglet around SS have been taken away largely by the leakage flow, so the accumulation of low-energy fluids is attenuated significantly in the corner between PS and casing wall, and the pressure distribution near PS of blade over tip presents similar to that of the original rotor. In other hand, due to the restriction of the extended tip winglet near SS, the accumulation of low-energy fluids also occurs in the corner between SS and casing wall, so the pressure tends to be a little larger than that of original rotor, which shows in Fig.4. However, because of the entrainment produced by the core of leakage vortex near SS of blade, the accumulation of low-energy fluids near SS of blade tip is weaker than that near PS of blade.



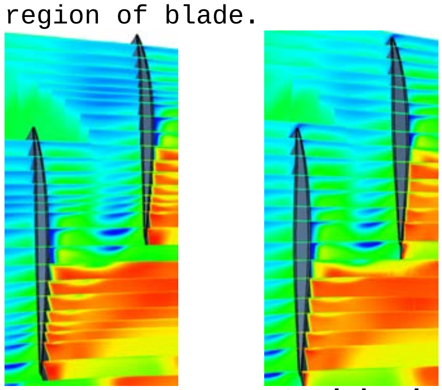
PS with tip winglet



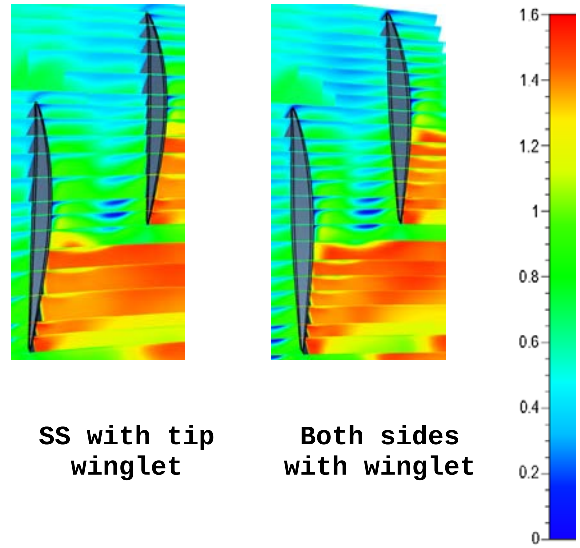
SS with tip winglet

Fig.15 the sketches of low-energy fluids migrations near blade surface of new rotors

Fig.16 presents the distributions of relative Mach number in tip region of rotors near stall point. In comparison with the original rotor, the low-velocity regions induced by leakage flow decrease in tip region of new rotors along streamwise direction, especially in the new rotor with tip winglet around SS. So it's evident from the change of the low-velocity regions that the influences of leakage flow to main flow have been attenuated in tip region of the new rotors due to the existence of tip winglet, even with the same back pressure at exit of rotors. In addition, it also can be seen clearly that the low-velocity region near SS of blade decreases in new rotor with tip winglet around SS, and it benefits to improve the flow in tip region of blade.



Origin **PS with tip winglet**



SS with tip winglet **Both sides with winglet**

Fig.16 The distributions of relative Mach number in tip region of rotor near stall point with the same back pressure

For the changes of relative Mach number in tip region shown in Fig.17, it's noted from the isolines of relative Mach number that the low-velocity region produced by leakage flow has decreased obviously in blade tip of new rotor with tip winglet around SS, and the minimum value of relative Mach number is much larger than that in original rotor. In contrast, the change of low-velocity region in new rotor with tip winglet around PS appears to be not obvious as that in the former new rotor. In the other hand, the low-velocity regions produced in latter part of passage are also present in Fig.17, All the low-velocity regions in three new rotors with tip winglet have decreased and the uniformity of the flowfields in latter part of passage has been improved as well. So it indicates again that the existence of tip winglet is beneficial to attenuate the influence of leakage flow in tip region of blade.

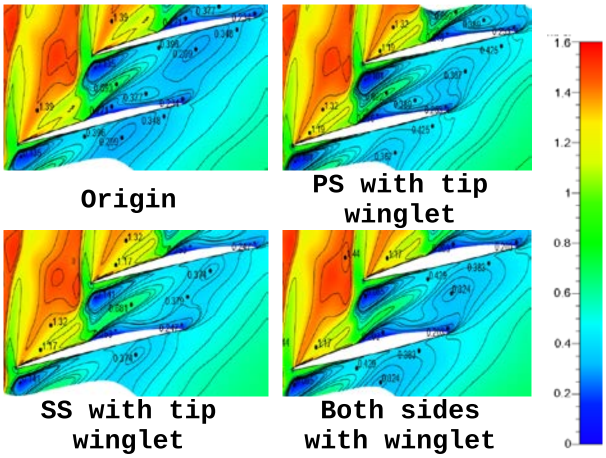


Fig.17 The contours of relative Mach number in blade tip region near stall point of rotor with the same back pressure

The distributions of entropy in tip region of rotors are present in Fig.18 near stall point with the same back pressure. As the influence of leakage vortex becomes weaker in new rotors due to the tip winglet, both the losses and the region for large entropy change decrease to some extent in comparison with the original rotor. Specifically, to the new rotor with tip winglet around SS, the high loss region becomes smaller obviously along streamlines of leakage flow in tip region of passage, and the losses near SS of blade reduces as well. However, the reductions of high loss region in new rotor with tip winglet around PS seem to be not obvious as that in former new rotor.

Fig.19 shows the distributions of static pressure near blade surface at different span of rotors near stall point. From the change of pressure distributions in new rotors, it can be seen that the winglet around SS of blade tip affects both the location and strength of shock wave in passage, and the change of shock wave appears to be much more obvious in the region approaching to blade tip. Specifically, the passage shock moves downstream in passage of the new rotor, especially in tip region of flowfield. In this process, the strength of shock wave decreases as well. However, the pressure distributions in new rotor with tip winglet around PS seem to be no obvious change in comparison with the original rotor.

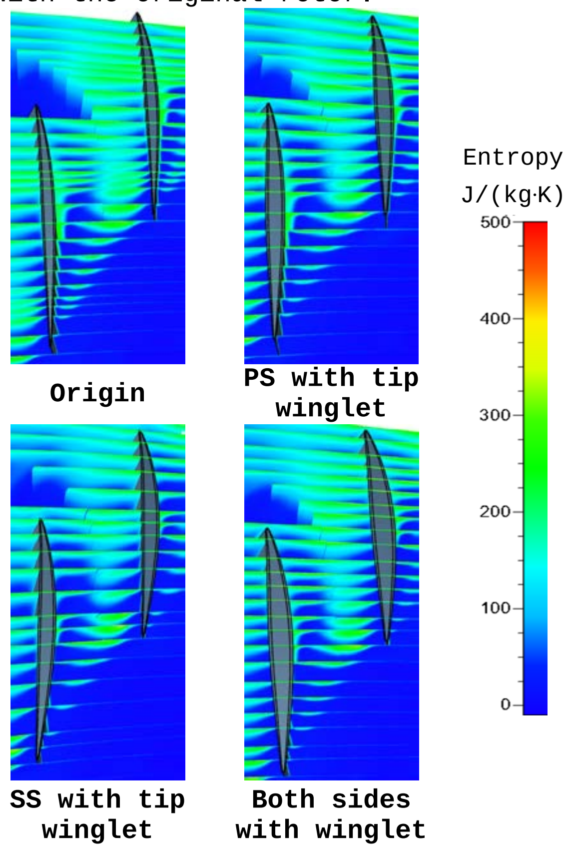
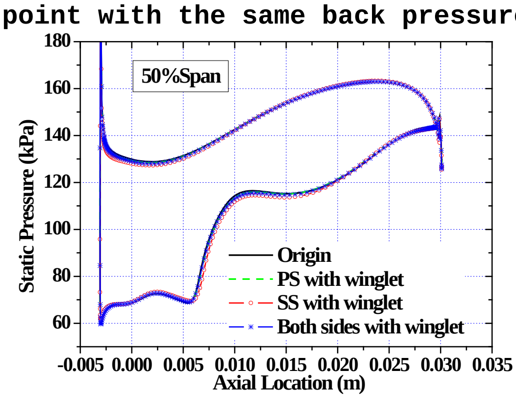


Fig.18 The distributions of entropy in tip region of rotor near stall point with the same back pressure



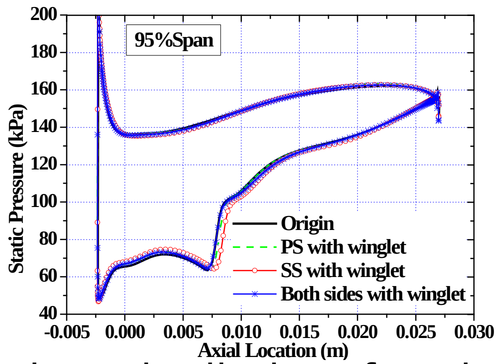


Fig.19 Distributions of static pressure near surface at different span of rotor near stall point with the same back pressure

Conclusions

The effects of tip winglet on overall performance and flow characteristic of highly loaded transonic rotors have been investigated in this paper. Three new rotors, with the same size of tip winglet around PS, SS and both sides of blade respectively, are simulated by numerical calculations to analyze the change of leakage flow, blade loading and loss distribution in tip region induced by tip winglet. The conclusions are as follows:

(1) The tip winglet benefits to stall margin improvement of high loading transonic rotor because it changes the trajectory of leakage flow in tip gap. In comparison, a maximum increase of over 9% appears in the new rotor with tip winglet around SS of blade. However, additional mixing and shearing losses are also produced in tip region, which is detrimental to the isentropic efficiencies of new rotors both at peak efficiency point and near stall point.

(2) With the same back pressure near stall point, the tip winglet decreases the angle between the vectors of leakage flow and main flow and pushes the leakage vortex core further away from PS, especially in the new rotor with winglet around SS. The change of trajectory for leakage flow induced by winglet is beneficial to attenuate the flow blockage in tip region and delay the occurrence of stall inception in new rotors.

(3) The accumulation of low-energy fluids in the corner between PS and casing wall produced by the restriction of extended tip winglet around blade PS increases the driving pressure difference of leakage flow along chordwise direction. In contrary, the accumulation of low-energy fluids in the corner near SS caused by winglet contributes to a little decrease of driving pressure difference near frontal part of the new rotor with SS tip winglet. The change of pressure difference has close relation to the strength of leakage flow and the losses induced by it.

(4) The strength of leakage flow has been attenuated obviously in new rotor with tip winglet around SS, and the influence range of leakage flow along streamwise is suppressed accordingly. However, in consideration of the shearing of leakage flow with extended blade tip and stationary casing wall, the aerodynamic losses in forward part of passage tend to be a little increase in tip gap of the new rotor, but it decreases in latter part of passage.

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