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THE INFLUENCE OF SUCTION-SIDE WINGLET ON TIP LEAKAGE FLOW IN COMPRESSOR CASCADE

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ABSTRACT

The effect of tip winglet on the aerodynamic performance of compressor cascade are mainly determined by the location of the tip winglet,the tip winglet geometry,the size of tip clearance,and the aerodynamic parameters of the cascade.In this paper,an extensive numerical study which includes three aspects has been carried out to investigate the effects of these influencing factors in a highly-loaded compressor cascade in order to give the guidance for the application of tip winglet to control the tip leakage in modern highly-loaded compressor.Firstly, the numerical method is validated by comparing the numerical results with available measured data. Results show that the numerical procedure is valid and accurate.Then,the cascade flow fields are interrogate to identify the physical mechanism of how suction-side winglet improve the cascade flow behavior. It is found that a significant tip leakage mass flow rate and aerodynamic loss reduction is possible by using proper tip winglet located near the suction side corner of the blade tip.Finally, an optimum width of the suction-side tip winglet is obtained by comparing the compressor performance with different clearances and incidences.The use of the suction-side winglet can reduce the pressure difference between the pressure and the suction sides of the blade and tip leakage velocity ratio.And the winglet also can compact the tip leakage vortex structure,which is benefit to decrease the loss of the tip secondary flow mixing with the primary flow.

INTRODUCTION

Rotor tip clearance is necessary for a free rotation of the rotor blade row.Large tip clearance is recognized to be detrimental to both the efficiency and stability of axial compressors(Freeman[1]).The pressure difference between the pressure and the suction sides of compressor rotor blade drives a leakage flow across the tip clearance,resulting in a strongly accelerating flow through the gap.The leakage fluid mixing with the passage flow,the annulus wall boundary and the blade surface boundary, rolls into tip leakage vortex. The tip leakage vortex has significant influence on the flow field structure and the energy transfer of the turbomachinery(Dring [2]).It is also one of the major sources of vortex noise generation by unsteady interactions with blade.(Dittmtar [3]).

In order to improve the performance of compressor, many efficient methods of tip leakage flow reduction have been introduced in the published works,such as casing treatment(Smith[4]),normal synthetic jet(JinwooBae[5]), curved (Han[6]) or swept(G.Scott[7]) blade technique and using plasma actuators(Scott Morris [8]) et al..These methods have shown the potential benefits of such an approach,but additional works needed to explore their range of applicability.Recently,a number of experimental and numerical studies consider the way of passive control of tip leakage by using the tip winglet on the blade tip in axial flow

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fan and axial flow turbines, which may be a new efficient method to reduce the losses associated with leakage and the leakage vortex.The idea using tip winglet on rotor was originally inspired by the winglet of aircraft wings proposed by Whitcomb[9] in 1976 to control the wing-tip vortex.The tip winglet was also used as a device for wind turbine to upgrade power coefficient(Shimizu [10]).Yen et al.[11] studied the exit flow fields and the global performance parameters of various types of axial flow fans with Particle Image Velocimetry,the experimental results demonstrate that the shrouded fan with winglets has the most stable flow field and the best fan performance.Camci and Akturk [12] analyzed the three dimensional mean flow at downstream of a ducted fan unit with various tip leakage mitigation schemes by varing the chordwise location and the width of the tip platform extensions using SPIV.The velocity profiles show significant gains in axial mean velocity component and reduction of tangential velocity component near the tip of the axial fan blade when a proper pressure side extension is used.Corsini et al.[13-15]investigated the application of profiled end-plates to the blade tips of a family of axial fans in fully-ducted configuration.They reported benefits in terms of aerodynamic and aeroacoustic performance as a result of the adoption of these modified blade-tip configurations. It was found that the tip geometrical modification markedly affected the multiple vortex leakage flow behaviour, by reducing the pressure difference within the tip gap and by altering the near-wall fluid flow paths on the blade surfaces.The new end-plate configurations provide a mechanism by which leakage vortex bursting can be avoided. Shavalikul and Camci [16] presented the results of a computational study of an axial turbine using pressure side extensions.The numerical simulation results showed that a significant tip leakage mass flow rate and aerodynamic loss reduction was possible by using proper tip platform extensions located near the pressure side corner of the blade tip.However, the fundamental mechanism of how winglet influence the tip leakage and improve the flow field is not clear yet.

Until now,it has not been proved whether the tip winglet is valid in compressor,and very few studies have been carried out on the effect of tip winglet on the compressor performance.The effects of tip winglet on compressor cascade aerodynamic performance are mainly determined by:(1)the tip winglet location;(2)the tip winglet geometry;(3)the tip clearance size;(4)the cascade aerodynamic parameters (e.g. incidence,solidity et al.),but how these factors influences the cascade performance is not clear yet.Therefore, this paper investigated numerically the secondary flow in compressor cascade with suction-side winglet at different tip clearances and incidences to obtain the general characteristics of specific tip leakage flow patterns.Numerical simulation of tip clearance may be more beneficial in understanding leakage flow physical than conventional experimental tools,because the flow field details in tip clearance are difficult to measure currently.

SUCTION-SIDE WINGLET

The current study deals with the concept of controlling the tip leakage by using suction-side tip winglet.A linear compressor cascade originally studied by Muthanna[17],Ma [18],Intaratep[19],Tian[20] at Virginia Polytechnic Institute and State University is simulated with no relative wall motion. Figure 1 shows the GE rotor B blade cross section used in their experiments,which has the round leading and trailing edges,and the thickness is maximum at 60 percent chord location.The blade with a chord 254mm and the blade spacing is 236mm,which corresponds to GE design condition.The stagger angle of the cascade is 33.1° and the aspect ratio is 1.To assess the benefit of suction-side winglet in compressor cascade with different clearances,for current study,the tip clearance heights are 0.8 percent,1.65 percent and 3.3 percent of the blade span respectively.To investigate the effects of cascade parameters on the performace of compressor cascade with suction-side winglet,incidences are varied from -10° to +10 ° to assess the benefits of suction-side winglet under different incoming flow conditions.

The suction side of the blade is extended in the tip region forming the specific suction-side winglet.Figure 2 shows the geometry of the suction-side winglet,the contour of the blade on the suction side surface is shaped smoothly so that only a lower effection of the local flow field and a low increase of the local stress should be expected.The winglet and the blade are manufactured in one part,the width of the winglet is proportional to the local thickness of the blade so that the extension size is smoothly from the leading and the trailing edge.Two values of the suction-side winglet's width are tested.The case of winglet's top width equal to 0.3 times of the blade thickness will be referred to as the SW0.3 case,while that of 0.5 times of the blade thickness will be called the SW0.5 case,and the baseline tip will be called the NW case.

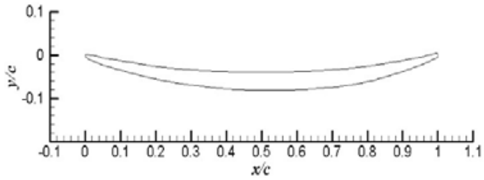


Figure1:Cross section of the GE rotor B blade used in the cascade[17]

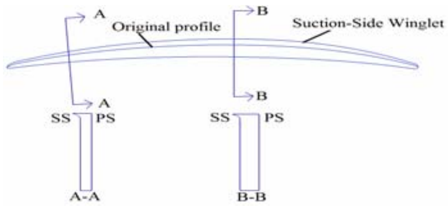
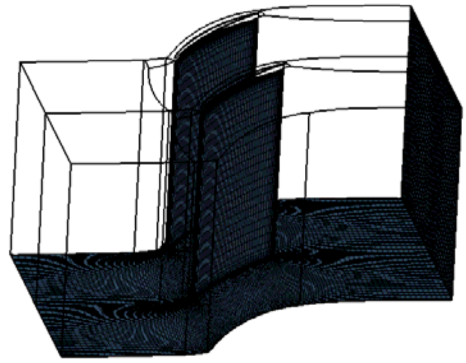


Figure2:Geometry of the suction-side winglet

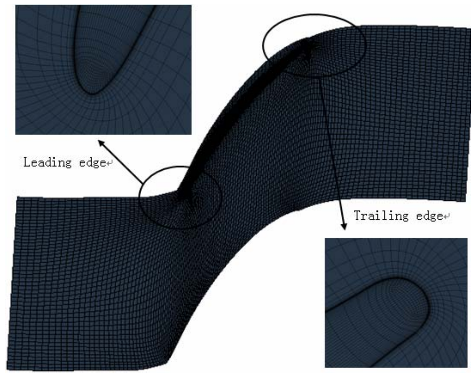
NUMERICAL CALCULATION METHOD

A commercial CFD software package,NUMECA was used to simulate the flow field of a compressor cascade.The Favre-Reynolds-averaged Navier-Stokes equations were discretized using a cell-centered explicit finite volume scheme. The steady-state flow solution was achieved at the convergence of a 4-stage explicit Runge-Kutta integration scheme.The discretization in space was performed using a second-order central discretization scheme with a fourth-order Jameson's type of artificial dissipation.To accelerate the residual convergence,a full multigrid strategy, local time stepping and implicit residual smoothing were performed. In the present work,turbulent phenomena were modeled using the Spalart-Allmaras turbulence model.

Figure 3 represents the grid used in the calculation, HI type structured blocks with grid-clustring in the near wall and tip gap region were generated automatically using IGG/Autogrid form NUMECA Int.Only one flow passage was modeled due to the periodicity of the cascade passage flow.In the axial direction,the mesh extended from 1.5 axial chord upstream to 1.5 axial chord downstream.The dimensionless distance,y+,on blade surface and casing wall was less than 5 to make the near wall mesh meet the requirement of the Spalart-Allmaras model in Numeca.The tip clearance was considered by adding an extra butterfly type block,and 17 grid nodes were distributed from the blade tip to the casing wall.A total of approximately 663,259 grid points had been selected



(a)3D compution grid



(b)Grid structure near the baseline tip

Figure3: Sketch of the grid for the simulation

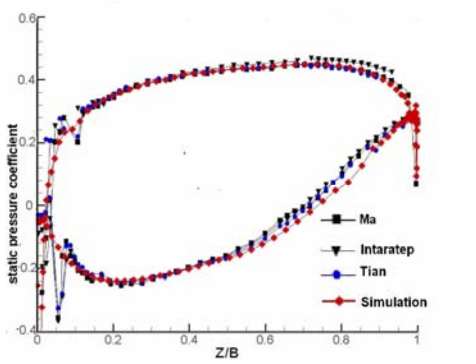
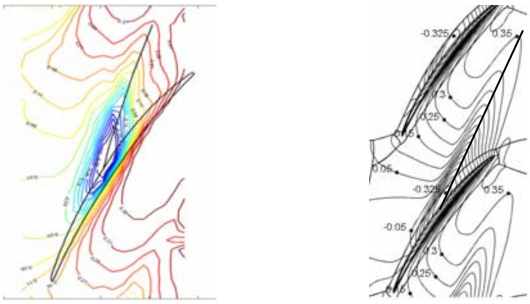


Figure4: The static pressure coefficient distribution at 50% blade span

to ensure the a good resolution of the viscous flow in the compressor cascade,while keeping the computational costs as low as possible.A grid independency study was performance,and results showed that the solution became grid independent at the present grid density.For the sake of brevity, grid independency study results are not presented in this paper.For the winglet tip considered in the present study,additionl grids proportional to the geometrical modifications were added.At the inlet,the total pressure,the total temperature and the air inlet angle were given the same as the experimental condition mentioned before. In the outlet,uniform static pressure was given.No-slip and adiabatic boundary conditions were used on the blade surfaces,winglet surface and the endwalls.The convergence criterion of the residuals was set to be 10^{-6}.



(a)Experiment[20] (b)Simulation

Figure 5: The static pressure coefficient distribution on casing

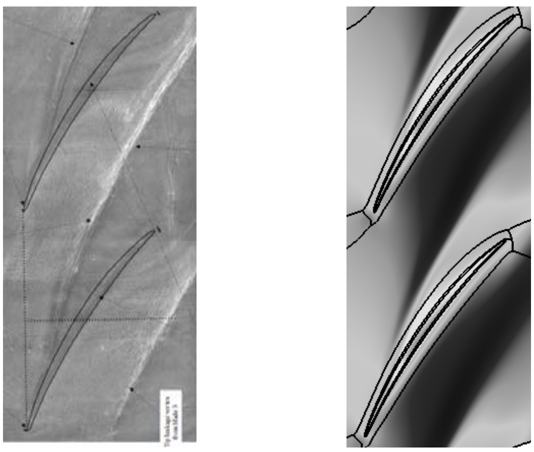


Figure6a:Experimental oil flow visualization on casing[17] Figure 6b:Computed shear stress distribution on casing

As we all know,the CFD code does not calculate with equal accuracy all features of turbomanchinery flow field.In order to validate the numerical simulation,we can compare the calculation results with the experimental results (Muthanna[17],Ma[18],Intaratep [19], Tian[20]).As seen from Figure4,the pressure distribution over the blade surface indicates that the current mesh topology is capable of resolving the gross features of the flow.The contours of the experimental casing static pressure distributions are shown in figure 5a and those of the computed in figure 5b.Excellent agreement for the locations and the magnitudes of the pressure trough on the endwall between measurement and the prediction.Experimental oil flow visualization on the casing is shown in figure 6a,and the computed shear stress distribution on casing is presented in figure 6b.The simulation captures appropriately the high wall shear stress region under the blade tip which is the result of acceleration of the flow through the gap and the region of low wall shear stress through the passage which shows the formation location and trajectory of the tip leakage vortex.

RESULTS AND DISCUSSION

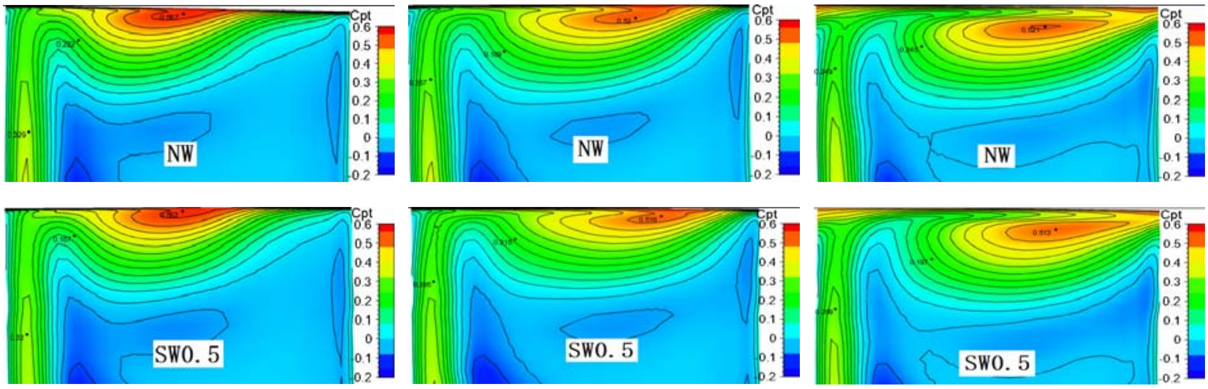
Effects of tip clearance sizes

The performace improvement of the compressor cascade resulting from the suction-side winglet is related closely to the size of blade tip clearance.The results of six numerical simulations of 3D compressor blade with and without suction-side winglet (SW0.5,NW)described earlier are present here.The tip clearance heights in the six cases are 0.8 percent,1.65 percent and 3.3 percent of the blade span respectively,for the cascade at 0° incidence in order to find the influences of suction-side winglet on aerodynamic performace of the compressor cascade with different tip clearances.

Figure 7 plots the distributions of total pressure loss coefficient at cascade exit area.The results show only the tip-side halves of the full planes traversed. The total pressure loss coefficient is defined as follows:

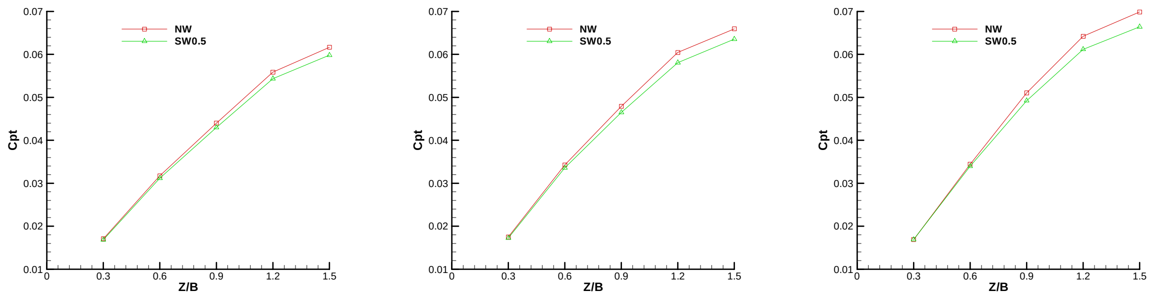
$$\xi = \left(P^*_{in} - P^*\right) \Big/ \frac{1}{2}\rho_{in} V^2{}_{in} \qquad (1)$$

The baseline cases are shown in the upper part of Figure 7,while the SW0.5 cases are shown in the lower portion of the same figure for direct comparison.The area contains the leakage vortex domainated zone and a significant portion of



（a） τ =0.8%h （b） τ =1.65%h （c） τ =3.3%h

Figure7:Distribution of total pressure loss coefficient at the exit plane



（a） τ =0.8%h （b） τ =1.65%h （c） τ =3.3%h

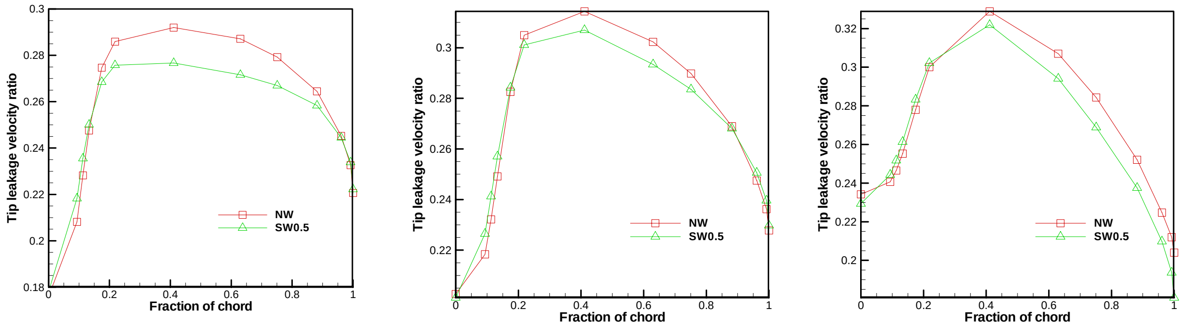
Figure8:Passage averaged total pressure loss coefficient values through the passage

the blade wake and the primary fluid between the wakes.The first impression is the tip leakage vortex,with high total pressure loss values in the region near the casing wall.As shown in Figure 7，without suction-side winglet,the influence of clearance size on the position of tip leakage vortex is significant.With the height of tip clearance increases,the core of tip leakage vortex is apparently shifted towards the pressure side and located further away form the the endwall.The amount of endwall fluid being sucked into tip clearance increases,and the tip leakage becomes stronger.The specific tip extension cases shown in figure 7 show a slight reduction on the strength of the tip leakage vortex.The dark red region in the core of the tip leakage vortex become a light red indicating that the high total pressure loss in the core of the baseline case is reducted slightly.Also,the leakage vortex in all cases entrains fluid of lower total pressure loss coefficient around the leakage vortex near the blade suction surface.This can be seen form the plume of lower loss coefficient fluid below and to the left of the tip leakage vortex.Due to the tip leakage vortexs in SW0.5 cases are further removed form the suction side of the blade,the entrained fluids make their way further around the tip leakage vortex.

The best approach to quantify the effectiveness of a suction-side winglet is to calculate the mass-averaged total pressure loss coefficient in the exit plane. The mass-averaged total pressure loss coefficient is described as follows:

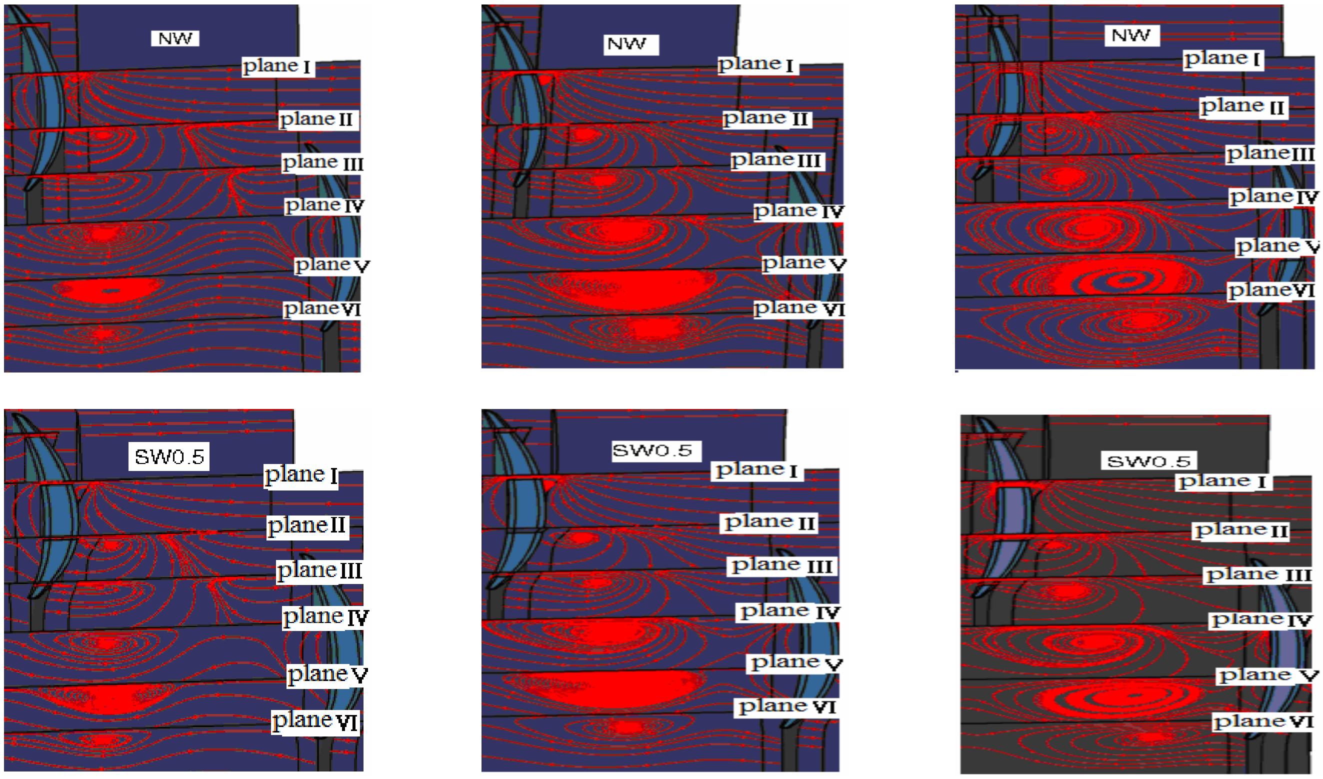
$$Cpt = \frac{\int_0^h \int_0^t \rho U \xi dxdy}{\int_0^h \int_0^t \rho U dxdy} \qquad (2)$$

Figure 8 demonstrates the variation of the passage-averaged total pressure loss values(mass averaged in the y-z plane) as axial chord vary. As shown in Figure 8,at 30 percent axial chord, the loss coefficients in the NW cases begin to exceed that of the SW0.5 cases.The rates of increase of the total pressure loss coefficient in the axial direction are also greater



（a） τ =0.8%h （b） τ =1.65%h （c） τ =3.3%h

Figure9: Chordwise distribution of tip leakage velocity ratio across the tip gap



（a） τ =0.8%h （b） τ =1.65%h （c） τ =3.3%h

Figure10:Leakage flow patterns in the visualization planes

in the baseline cases.When the tip clearance height is 3.3 percent of the blade span,the values of the total loss coefficient at 150 percent axial chord is roughly 4.95 percent lower in the SW0.5 case.

As a quantitative evalution,the local over tip leakage velocity ratio (divided by the inlet velocity of the free stream)across the tip platform is plotted in function of chord length in Figure 9.According to Rain's method[21],using the camberline as the reference for tip leakage flow,the leakage velocity is defined as the component normal to the blade camberline. The tip leakage velocity ratio continually increases from the leading edge to a maximum value around the 40 percents of chord for the baseline tip with three tip clearances.For all three tip clearance cases,the suction-side winglet provide a considerable gain in reducing tip leakage velocity ratio.When the tip clearance height are 0.8 percent and

1.65 percent of the blade span,the SW0.5 case is more efficient to reduce the velocity ratio between 20 percent and 80 percent of the chord. As the height of tip clearance increases to 3.3 percent of the blade span,a highly effective leakage reduction is obtained for the chord area from 30 percent of the chord to the trailing edge.

The tip leakage flowfield is highly complicated,in which the leakage vortex interacts with the nonuniform main flow and boundary on the casing wall.Zhang [22]gives the criterion of vortex stability as following:

$$\lambda = \frac{u_\infty}{L}(1 - Ma_z{}^2)\left(\frac{\partial w}{\partial z}\right)_0 \qquad (3)$$

$$\left(\frac{\partial w}{\partial z}\right)_0 = -\left(\frac{1}{\rho w}\frac{\partial p}{\partial z}\right)_0 \qquad (4)$$

Where λ is the characteristic value to judge the stability of the vortex(λ>0,the vortex is stable; λ<0,the vortex is unstable),z represents the direction of the vortex axis,w represents the velocity of vortex axis, Ma_z is the Mach number of vortex axis. u_∞ and L are characteristic velocity and character length,respectively.For current study of tip leakage vortex, Ma_z<1.And the cascade flow is in a diffusion condition with a large adverse gradient,so $(\partial p/\partial z)_0 > 0$, $(\partial w/\partial z)_0 < 0$, λ<0.Therefore,The tip leakage vortex is unstable,and the tip leakage vortex core will breakdown during its development from the blade suction side to the flow channel.To investigate the winglet effect on the structure of tip leakage , the leakage flow patterns on six crossflow planes nearly perpendicular to the tip leakage vortex core,are shown by planes Ⅰ,Ⅱ,III,Ⅳ,Ⅴand Ⅵ in Figure 11.The first impression from the plots in Figure 11 is the generation,development, breakdown and dihffusing of the tip leakage vortex.The tip leakage flows from the pressure side to the suction side of the blade and then mixes with the main passage flow generating tip vortex,as the tip vortex stretches downstream,the center of the tip vortex is gradually moving far away from suction side surface of the blade and the casing wall.At the planeⅤ,the tip leakage vortex core expand to a larger size as a blockage to the primary flow in the passage.For the cascade with suction-side winglet,the intensity of the tip leakage vortex is reduced at different planes,and the shape of the tip leakage vortex core is flatter and more compact than the baseline case,which may caused by radial blade force from the suction side entension. The flat and compact tip vortex is helpful to reduce the scope and the mass of the interaction between the tip vortex and the main flow.Furthermore,the tip vortex at a location slightly further away from the suction side of the blade than the baseline tip as shown in Figure 11, which is benefit to reduce the leakage vortex to roll up more low-energy fluid near the blade suction/endwall corner.

Table1.Comparison of the cascade mass-averaged total pressure loss coefficient at different incidences

	-10°	-5°	0°	+5°	+10°
NW	0.1453	0.0668	0.0642	0.0930	0.1279
SW0.3	0.1369	0.0564	0.0620	0.0929	0.1315
relative change	-5.78%	-15.5%	-3.43%	-0.1%	+2.81%
SW0.5	0.1368	0.0557	0.0612	0.0923	0.1309
relative change	-5.84%	-16.62%	-4.67%	-0.75%	+2.35%

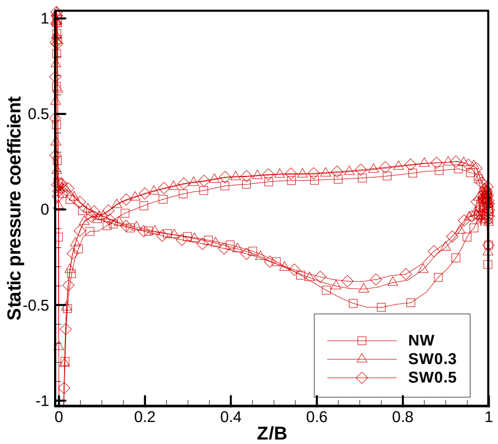
Effects of Incidences

The effect of the incidences are also studied in the cascade with and without suction-side winglet with the height of clearance 3.3 percent of the blade span.Similar to Figure 8,the mass-averaged total pressure loss coefficients at the cascade outlet at different incidences are given in Table 1.Once again,NW in theTable 1 represent the baseline tip case without suction-side winglet.The total loss coefficient of the cascade without suction-side winglet is sensitive to the variation of the incidence.At the incidences of 0°,-5° and-10°,the total loss of the cascades with suction-side winglet decrease efficiently.While keeping the flow incidence constant,the optimal winglet width corresponding to the minmum total loss of the cascade exit,i.e. SW0.5 case.The total loss reduction reaches the maximum value of 16.62% when the incidence is -5°.However,at positive incidences,the aerodynamic performances of the cascade are improved little and even deteriorated.Combined with the data in Table 1,we can draw the conclusion that the suction-side winglet is an efficient way to improve the aerodynamic performance of the high-loaded compressor cascade at zero and negative incidences.Therefore,the following analysis keep more attention on the zero and negative incidences conditions.

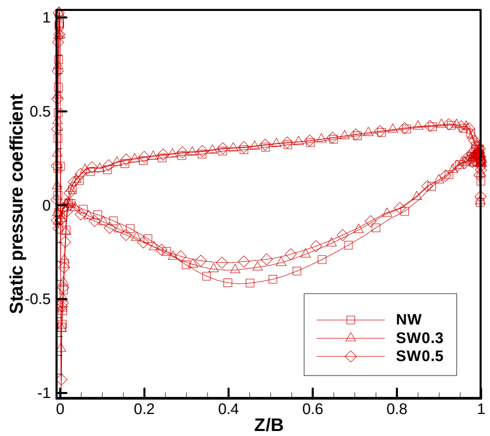
In Figure 11,the variations of static pressure coefficient are shown for the cascade with and without suction-side winglet.Results are presented at 98% span for the incidence values of -5°, 0°.For the baseline case,shown in figure 11(b),it can be found the suction peak is located at about 45 percent of axial chord at 0° incidence,which is related to the generation of the tip leakage flow and the motion of the corresponding tip leakge vortex.As the tip leakage vortex moves away from the suction side of the blade,its influence decreases gradually.At the negative incidence,the minimum pressure near the blade tip shifts towards the trailing edge to about 75 perenct of axial chord,which is a consequence of the tip leakage vortex tending to move further downstream. For the cascade with suction-side winglet,the static pressure on the pressure surface slightly increase at the negative incidence,and the influence of the suction-side winglet on the static pressure of the pressure surface can be neglected at 0° incidence.At the zero and negative incidences,the suction-side winglet significantly increases the static pressure on the suction surface due to the reduction of tip leakage vortex can be identified.The reducation of the pressure difference between the pressure and the suction side is benefit to reduce the leakage mass flow so that the tip leakage vortex and associated mixture losses are reduced.

Five planes spaced equally from 10% to 90% chord are selected to investigate the tip leakage velocity ratio at the tip clearance exit,as shown in Figure 12.As mentioned before,the leakage velocity is defined as that the component normal to the blade camberline.Without suction-side winglet,when the incidence angle decreases from 0° to -5°,tip leakage ratio of the planes near the leading edge decreases,but the velocity profile at the 90% chord increases significantly,which coincides with the distribution of the static pressure on the blade tip surface in Figure 11.Due to the effectiveness of the suction-side winglet,at negative incidence,it can be observed that the velocity ratio at the gap exit in the aft part of the blade decreases significantly,but tip leakage velocity ratio near the leading edge slightly increases.At 0° incidence,high leakage velocity ratios still occur in the middle of the blade,but they are much lower than those in the case without suction-side winglet.

In Figure 13,the mass-averaged total pressure loss

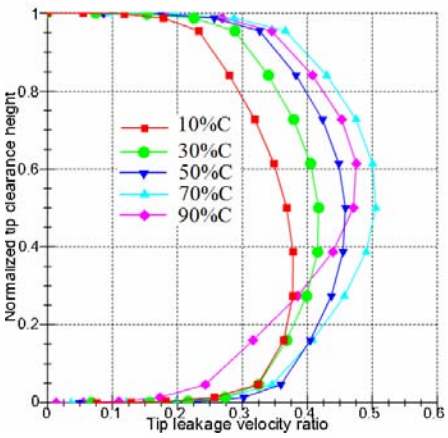


(a)-5° incidence

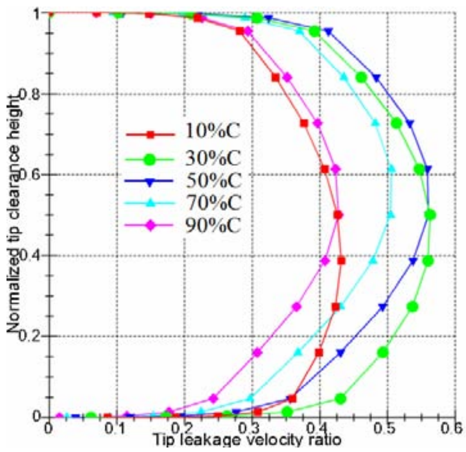


(b)0° incidence

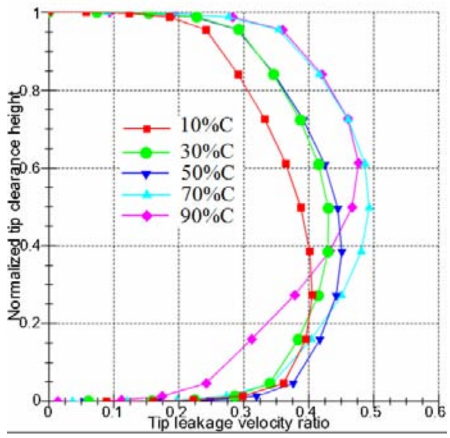
Figure11: The static pressure coefficient distribution at 98% blade span in different incidences



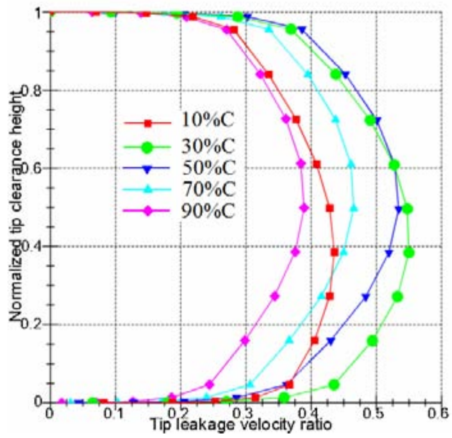
NW（-5° incidence）



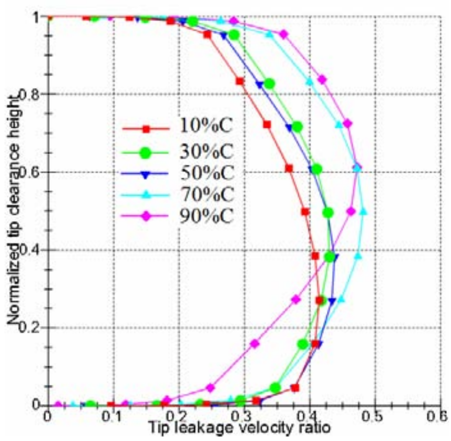
NW（0° incidence）



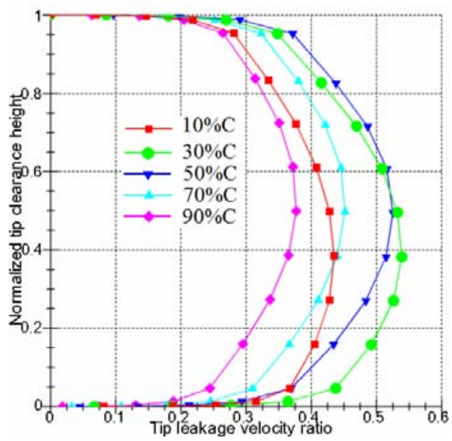
SW0.3(-5° incidence)



SW0.3(0° incidence)

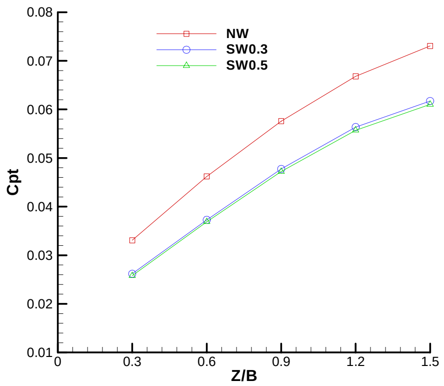


SW0.5(-5° incidence)

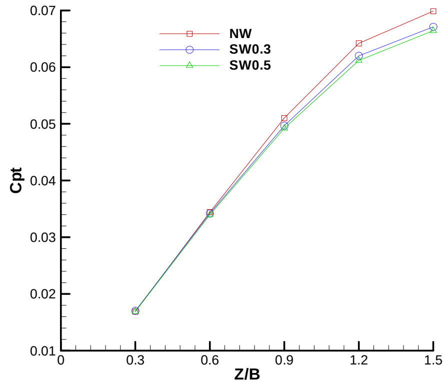


SW0.5(0° incidence)

Figure12: Tip leakage velocity ratio of the gap exit at different chordwise locations



(-5° incidence)



(0° incidence)

Figure13:Passage averaged total pressure loss coefficient values through the passage

coefficient in sections that are placed perpendicular to the axial direction is depicted.It can be seen that the loss is growing with higher axial chord position.Considering the comparison of the cascade with and without suction-side winglet,it is obvious that the change of mass-averaged total pressure loss coefficient.The suction-side winglet design provides the most significant gain in term of controlling the aerodynamic losses of the cascade at negative incidence.The flow computations for the SW0.5 case show a slight better loss control than the SW0.3 case.

CONCLUSIONS

The effectiveness of an passive tip clearance control method based on applying a new design suction-side winglet on blade tip,which to cause only small changes in eigenfrequencies and mechanical stresses of the blade,is investigated in this paper.The effects of the suction-side winglet width,the size of tip clearance and the incidence are investigated by the numerical method without taking into account the effect of the casing wall relative motion.The main conclusions based on numerical simulation results are listed as follows:

(1)For all tip clearance cases,the suction-side winglet can reduce the total loss of the compressor cascade.Losses become less sensitive to the clearance when the tip winglet is apply.

(2) The suction-side winglet is an efficient way to reduce the tip leakage velocity ratio across the tip gap,the leakage mass flow should be reduced so that the tip leakage vortex and associated mixture losses are reduced.

(3) The suction-side winglet pushes the core of tip leakage vortex further away from the suction side surface of the blade, which is benefit to reduce the leakage vortex to roll up more low-energy fluid near the blade suction/endwall corner. Moreover,the shape of the tip leakage vortex core is flatter and more compact than the baseline case.

(4) The influence of the incidence on tip leakage controlling of suction-side winglet is significant, the suction-side winglet is an efficient way to improve the aerodynamic performance of the high-loaded compressor cascade at zero and negative incidences.

(5) Due to the reduction of the pressure difference between the pressure and the suction sides of the blade by the suction-side winglet,tip clearance mass flow velocity is reduced and is affected by the incidence angle.

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NOMENCLATURE

B =axial chord
C =blade chord
H =blade span
τ =tip clearance height
ξ = total pressure loss coefficient
Cpt = mass-averaged total pressure loss coefficient
y+ =non-dimensional turbulence wall function
x,y,z =Cartesian coordinates
P^* = total pressure
P = static pressure
λ = the characteristic value of the vortex stability

u_∞ =characteristic velocity

L = character length

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