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EFFECTS OF LEANING AND CURVING OF BLADES WITH HIGH TURNING ANGLES ON THE AERODYNAMIC CHARACTERISTICS OF TURBINE RECTANGULAR CASCADES

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ABSTRACT

To intensively understand the effects of the origination and development of centralized vortices on the aerodynamic characteristics of turbine rectangular cascades with high turning angles, an experiments with 5-hole micro spherical probes, accompanied by color helium bubble flow display, were carried out. The measurement planes are arranged as 3 before, 6 in and 1 after, the cascade. The experiments reveal that the origination and development of horseshoe vortices and passage vortices as well as the interaction of the latters almost dominate the whole flow field of traditional linear cascades. Lean linear cascades favor the horseshoe vortices and passage vortices in the acute angle zone, and impede those in the obtuse angle zone. So it is a logical result to adopt the negatively curved blades, whose pressure surfaces and both endwalls compose both obtuse angles respectively, to improve the cascade aerodynamic characteristics.

NOMENCLATURE

h=blade height
z=distance of measuring point from lower endwall
$\bar{h}$=relative blade height (z/h)
p=static pressure
i=number of measuring stations
α_1=airflow angle measured from the axial direction
α_{1p}=cascade geometrical outlet angle
p=pressure surface of a blade
s=suction surface of a blade
c_u=pitchwise averaged tangential velocity
$(c_u)_{\varepsilon=0^\circ}$=mass flux averaged totaltangential velocity of traditional cascade
$\bar{c}_u$=tangential velocity coefficient, $\bar{c}_u=c_u/(c_u)_{\varepsilon=0^\circ}$
t_y=distance of measuring point from suction surface in pitch direction
t=distance between suction surface and pressure surface in pitch direction
$\bar{t}_y$=relative distance in pitch direction(t_y/t)
$\bar{p}$=static pressure coefficient, $\bar{p}=(p_i-p_1)/(p_0^*-p_1)$
ξ=energy loss coefficient, $\xi=[(p_i/p_1^*)^{\frac{k-1}{k}}-(p_i/p_0^*)^{\frac{k-1}{k}}]/[1-(p_i/p_0^*)^{\frac{k-1}{k}}]$
k=specific heats ratio

SUBSCRIPTS AND SUPERSCRIPTS

0=inlet parameter of a cascade
1=parameter behind a cascade
$*$=Stagnation parameter
i=parameter at a measuring station
m=pitchwise averaged parameter
t=mass flux averaged total parameter

INTRODUCTION

Blades with low aspect ratio and high turning angle are widely used in guide cascade of adjust stage, rotor cascades with low-reaction of high pressure stages of a steam turbine and in a gas turbine with high-pressure ratio. Even through this kind of blades has obvious advantage in mechanical property and cost, the following problems usually exist: the centralized vortices of high intensity and large scale produced by the big airflow turning angles, especially the leading edge vortices composed mostily by horseshoe vortices, and the upper and lower passage vortices almost govern the whole flow field, as shown by Langston (1977). These vortices not only cause the 3-d seperation of the endwall boundary layer, dissapating the airflow energy and raising secondary flow losses noticeablely, but also change the airflow outlet angles and hence the incidences on the next cascade (Sieverding, 1985). A good design should ensure that for equal turbine work, the unfavorable effect of secondary flows be reduced to the minimum, and the secondary flow losses and outlet angles be predicted accurately (Harrison, 1990). So it is necessary to study the model of flow through the cascade with blades with low aspect ratio and high turning angle, and the methods to reduce the secondary flow losses.

Using curved blades can efficiently reduce the secondary flow losses. In

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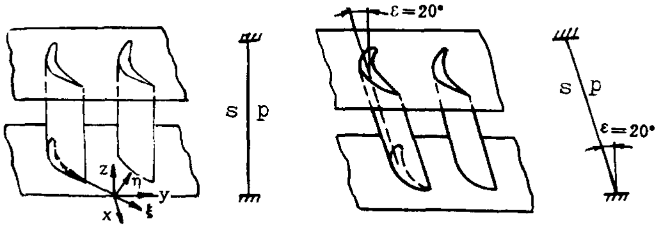
cascades with low turning angle, the transverse secondary flow losses in the end parts of blades take the main portion of the total losses. When lean linear blades are used in the type of cascade, the flows in the acute angle zone between pressure surfaces and endwalls are improved(Wang, 1988). The positively curved blade, whose pressure surface and both endwalls compose both acute angles respectively, introduces the improvement in the acute angle zone into a cascade(Han, 1990). the present paper discusses the loss mechanism in the cascades with high turning angles and effects of blade leaning on the flows in the acute and obtuse angle zones, trying to find the curving method of blades with high turning angle to reduce the losses.

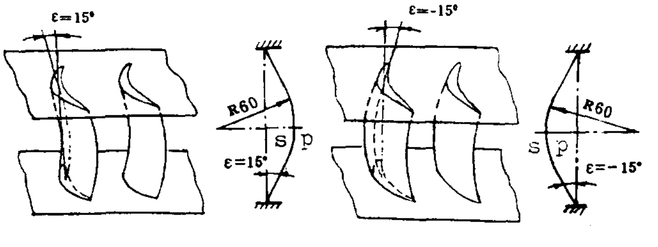
EXPERIMENT MODELS

The experiment was finished in a low-speed plane cascade wind tunnel. The tested cascades are: (a) traditional linear blade cascade; (b) lean linear one ($\varepsilon=20°$); (c) positively curved one ($\varepsilon=15°$); (d)negatively curved one ($\varepsilon=15°$). 10 measurement planes shown in Fig. 2 cover the space before and after the cascades. The flow parameters along the directions of pitch and blade height are measured by 5-hole spherical probes. The other geometry and aerodynamic parameters of tested cascades are: chord, $b=120mm$; axial chord, $B=105mm$; blade height, $h=110mm$; aspect ratio, $h/b=0.917$; pitch-chord ratio, $t/b=0.667$; inlet aiifiow angle, $\alpha_o=64°$; geometry outlet angle, $\alpha_{1p}=64.5°$; inlet total pressure, $P_o^*=5773p_a$; Reynolds Number and Mach Number at the midspan of outlet plane, $Re=6.4\times10^5$ and $M=0.26$, respectively.

The coordinate systems used are x, y, z and ξ, η, z. Here x is for axial, y pitchwise, and z blade height direction, while ξ is in the streamwise direction at midspan midpitch, and η is perpendicular to both ξ and z, respectively (Fig. 1, a). The velocity components v, w in the η and z direction then represent the secondary velocities, $v=c\cos\sigma\sin(\alpha_{1p}-\alpha_1)$, $w=c\sin\sigma$, where c is the outlet airflow velocity, σ is the angle between c and the plane parallel to the endwall, α_{1p} is the cascade geometry outlet angle, α_1 is the outlet airflow angle. Velocity vectors in plane perpendicular to flow direction in Fig. 4 are the vectorial sums of v and w, and streamwise vortisity contours are obtained by finite differentiations of v and w.



(a)Traditional Linear blade Cascade (b)Lean Linear blade Cascade



(c)Positively curved blade Cascade (d)Negatively Curved blade Cascade

Fig. 1 Tested Cascades and shapes of Profile stacked Lines

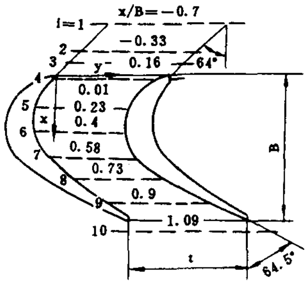


Fig. 2 Measurement Planes

EXPERIMENTAL RESULTS AND DISCUSSION

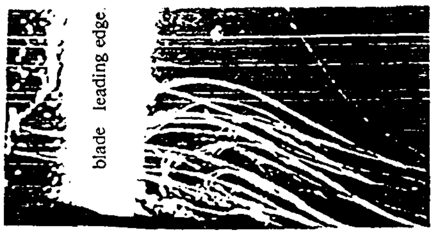
Flows in Upstream and at Leading Edge

To study the influence of types of cascades on the inlet boundary layers, the parameters in the boundary layer are measured without cascades and with differennt cascades. The measurement results are shown in Tab. 1. From the table it is seen that the parameters in the upper inlet boundary layer are equal to those in the lower inlet boundary layer whenever cascade is not present, or traditional linear blade, prositively curved blade, negatively curved blade cascade is present, meaning the inlet flowfield is rather even. When different cascade are mounted, or no cascades, the parameters of the boundary layers in the table are different, which results from differnent axial pressure decrease produced by using different cascades.

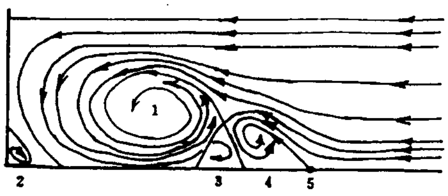
TAB. 1 Measurement Results of Boundary Layers on Inlet Endwalls

	Without cascade	Traditional cascade	Acute angle zone of lean blade cascade	Obtuse angle zone of lean blade cascade	Positively curve blade cascade	Negatively curved blade cascade
Thickness δ(mm)	23.6	26.9	34	25.8	33.2	24.6
Displacement thickness δ* (mm)	2.5	2.9	3.6	2.8	3.5	2.7
Shape factor H	1.47	1.45	1.47	1.52	1.5	

Inlet boundary layers develop into leading edge vortices, mainly composed by horseshoe vortices, in terms of 3-d seperation at the saddle points ahead of cascade leading edges. Some reference concerned proposed that it is difficult to measure the leading edge vortices by 5-hole probe. But from our measured result one can see the slight rotation of velocity components in the plane perpendicular to the main flow, and the deformation of inlet boundary layers, which agree the color helium bubble flow display of the geometry similarity amplified traditional linear blade cascade in a large scale wind tunnel. Fig. 3 shows leading edge vortices include two zones, zone 1 consisting



(a)Color Helium Flow Display



1. Horseshoe Vortices 2. Corner Vortices 3. Counter Vortices
4. Seperation Vortices 5. Seperation Points

(b)Flow Model near Leading Edge

Fig. 3 Flow Model near Leading Edge of Cascade

of horseshoe vortices 1 and corner vortices 2, and zone 2 of counter vortices 3, seperation vortices 4 and seperation points 5, which agrees the vortical structure in reference (Ishii, 1986). When leading edge vortices run through leading edges of a blade, the horseshoe vortex is split into two legs which are called the pressure side leg and the suction side leg respectively, and continue going into the passage. The other vortices are dissapated by the viscosity.

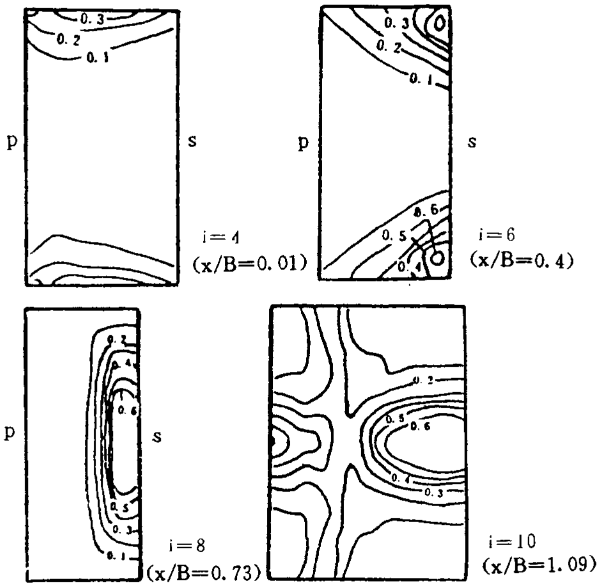
Flows in Passages

At the downstream of a cascade, one can see the pressure side leg of horseshoe vortex near lower endwalls, while going into its passage in the anti-clockwise direction, and the other leg in the clockwise direction. Measurement plane 4 in Fig. 4 shows clearly that the scale and intensity of horseshoe vortices in the acute angle zones of the lean blade cascade and positively curved blade cascade are bigger than those of the traditional cascade. In the obtuse angle zones of the lean blade cascade and negatively curved cascade the opposite cases hold.

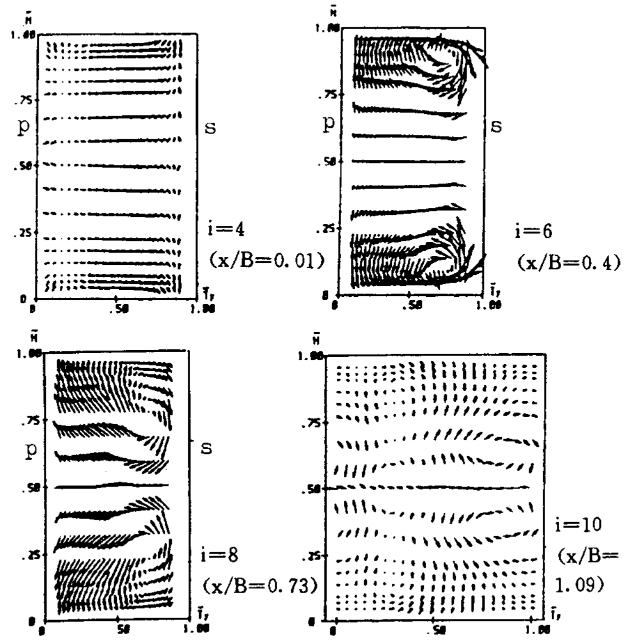
Three factors determine the origination and development of horseshoe vortices; inlet boundary layer thickness, streamwise adverse pressure gradient and the stagnation pressure gradident in the normal direction of endwalls. Any one of the three, if intensefied, will favor the seperation of boundary layers and the development of horshshoe vortices, and move the seperation saddle point A and the seperation line S to the upstream (Fig. 5). Because the inlet boundary layers in the acute angle zones of lean blades and positively curved blades are thicker, and the inlet adverse pressure segments is longer and adverse pressure gradients are greater(Fig. 6), the boundary layer saddle points are farther from the leading edges, and the scale and intensity of the horseshoe vortices in the same measurement plane are bigger, compared with those of traditional cascade. The opposite case holds for the obtuse angle zones of lean blade cascade and negatively curved cascade.

The pressure side leg of the horseshoe vortex companices the suction side leg of the adjacent blade going into the same passage. Both of them roll toward the suction side by the transverse pressure gradient. As the pressure side leg rolls up the main portion of the lower energy airflows in inlet boundary layers, new boundary layers are formed behind the seperation line. When horseshoe vortices reach the suction side corner, the lower energy airflow in new boundary layers, driven by transverse pressure gradient to here, join them and roll towards the middle of the passage and pressure side of the blade, developing into high intensity and large scale passage vortices (Fig. 4, b,c, measurement plane 6). Because the pressure side leg coincides with the core of the passage vortex, the passage vortex, when is formed, has high rotation velocity such that a low pressure point and a peak of energy loss appear near the core. The suction side leg, as it rotates in the opposite direction of the passage vortex, gradually dissolves by the shear force when meeting with the passage vortex.

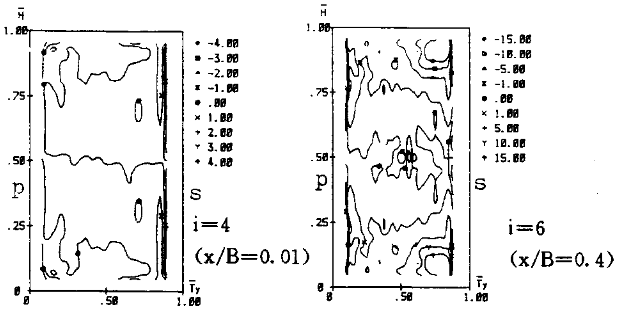
Four parameters decide the origination and development of passage vortices. They are the intensity of horseshoe vortices, transverse pressure gradient in the passage, pressure disstribution along blade height and the streamwise adverse pressure gradient. In cascades with high turning angle, the

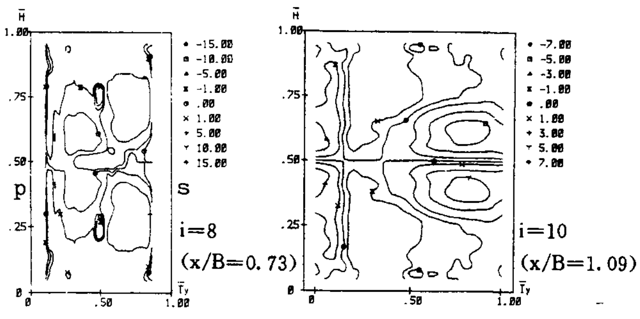


(a)Loss Coefficient Contours of Traditional Linear Blades

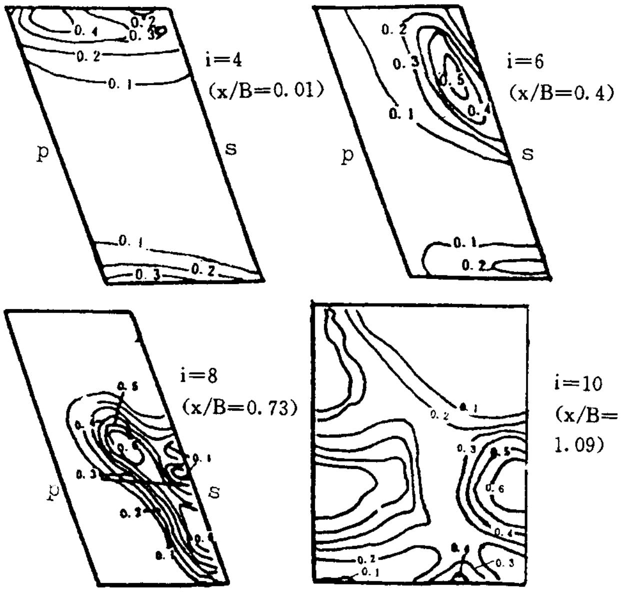


(b)Velocity Vectors in Planes Perpendicular
to Flow Direction of Traditional Blades

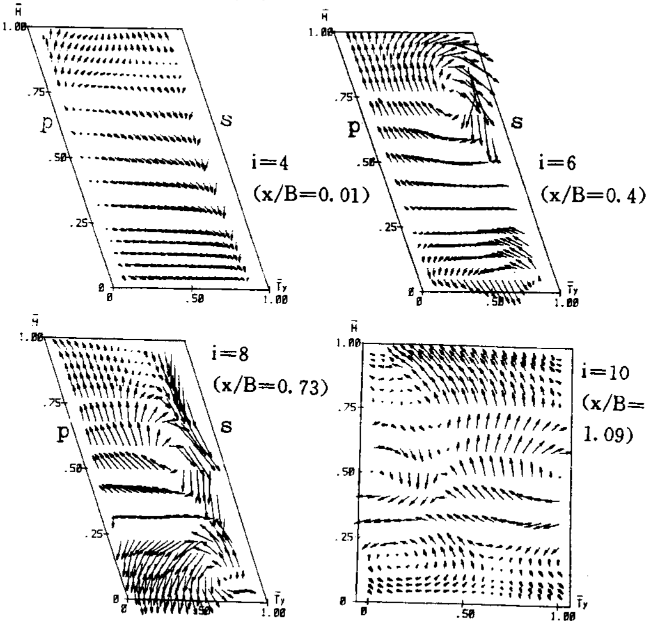




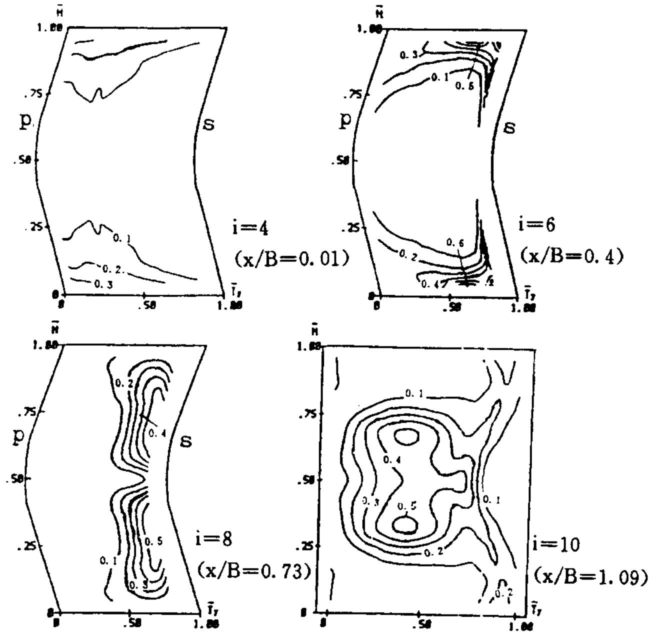
(c)Streamwise Vorticity Contours of Traditional Blades
(The vorticities in the clockwise direction are negative, the ones in the anti-clockwise direction are positive.)



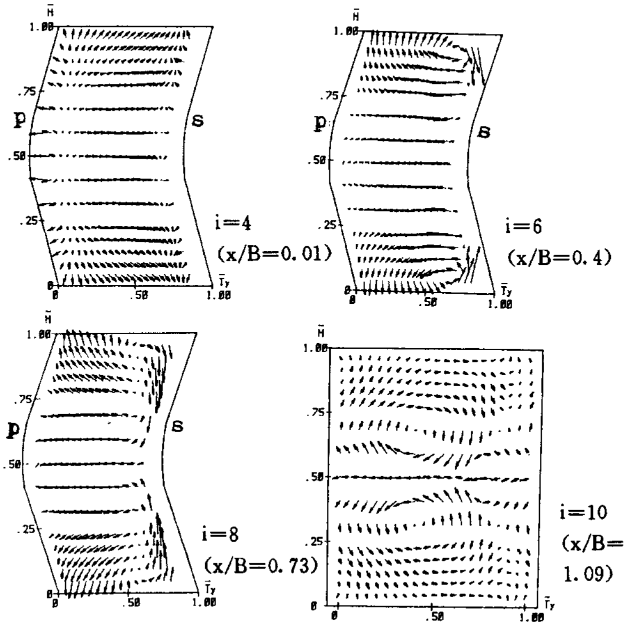
(d)Loss Coefficient Contours of Leane Linear Blades



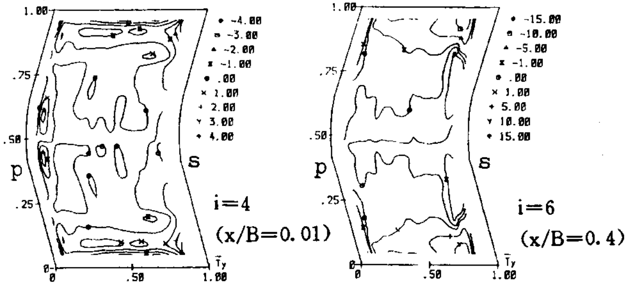
(e)Velocity Vectors in Planes Perpendicular to Flow Direction of Lean Linear Blades

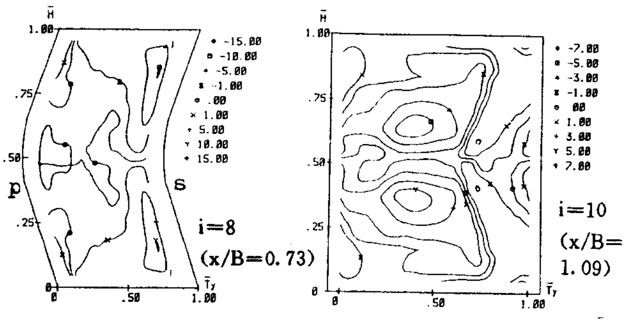


(f)Loss Coefficient Contours of Negatively Curved Blades

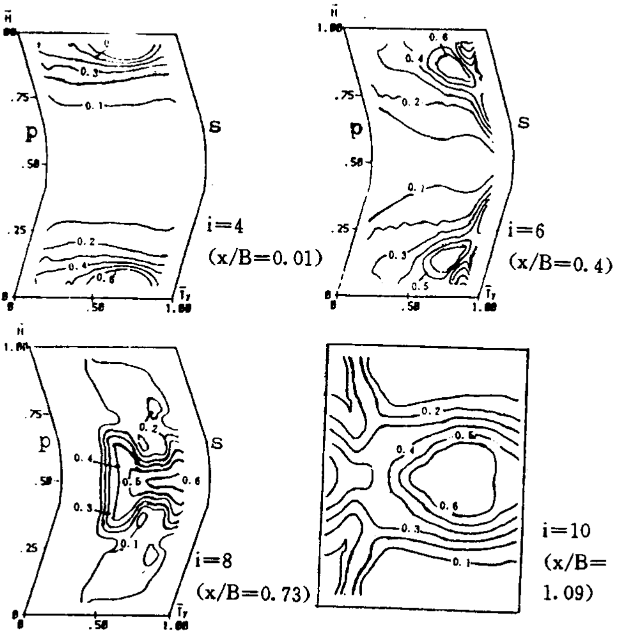


(g)Velocity Vectors in Planes Perpendicular to Flow Direction of Negatively Curved Blades

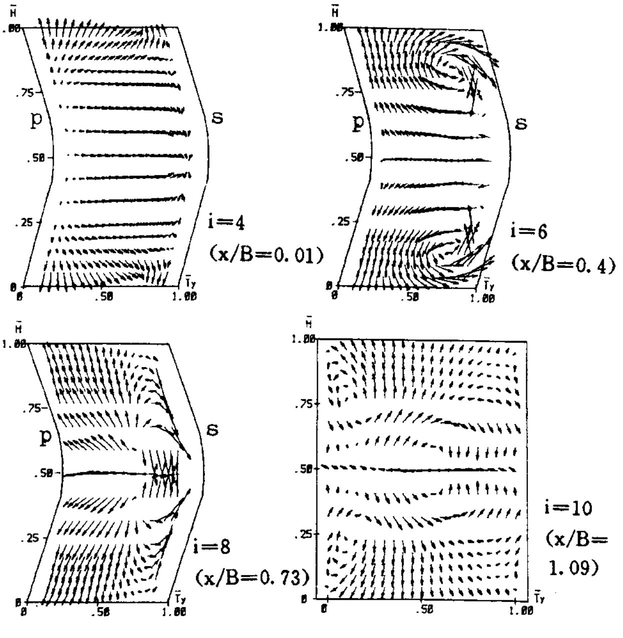




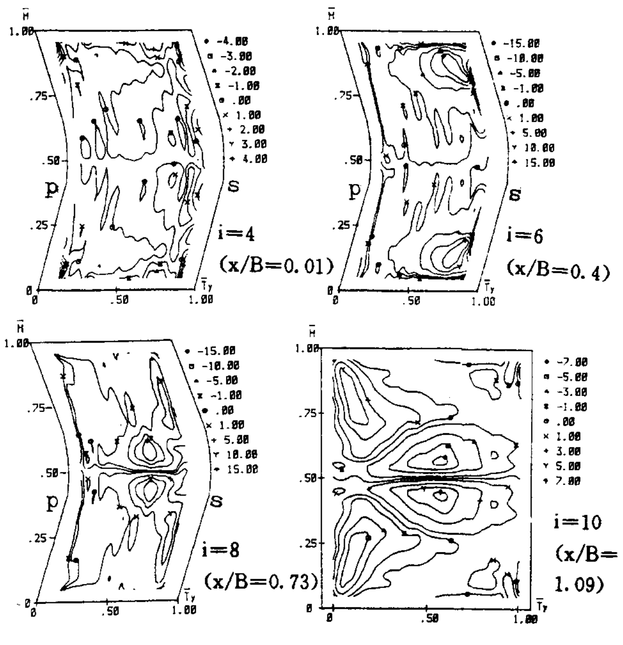
(h)Streamwise Vortisity Contours of Negatively curved Blades



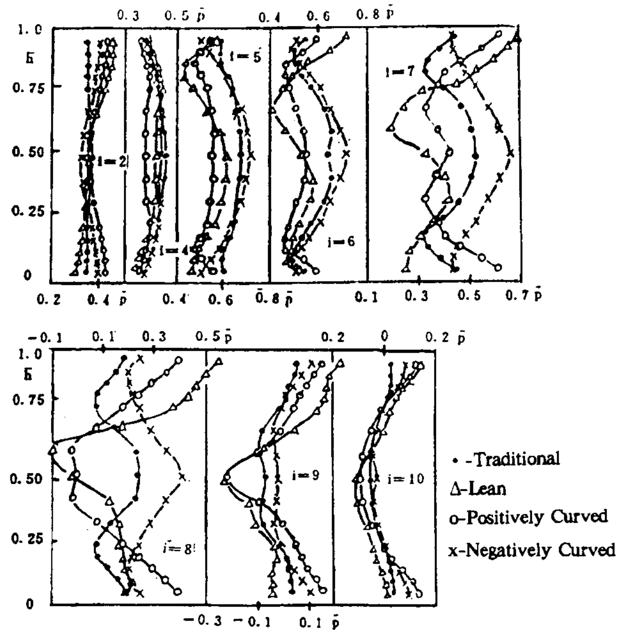
(i)Loss Coefficient Contours of Positively Curved Blades



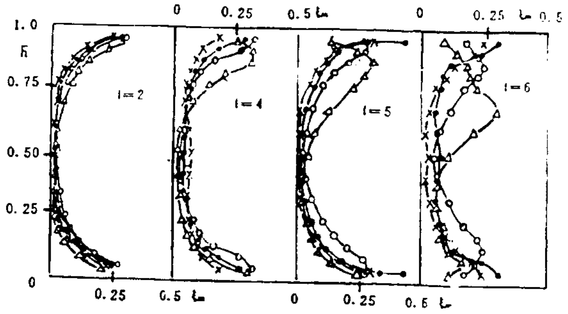
(j)Velocity Vectors in Planes Perpendicular to Flow Direction of Positively Curved Blades

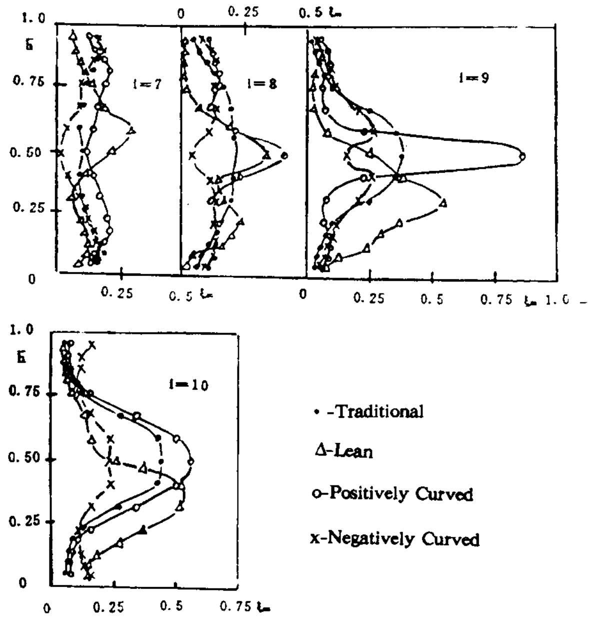


(k)Streamwise Vortisity Contours of Positively Curved Blades



(l)Pitch Averaged Static Pressure Coefficient Distribution along Blade Height in the Passge





(m)Loss Coefficient Distribution along Blade Height

Fig. 4 Aerodynamic Parameter Distribution in Measurement Plans

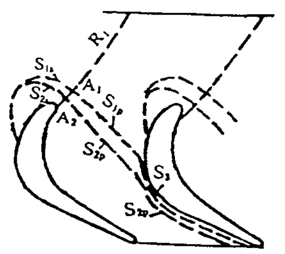
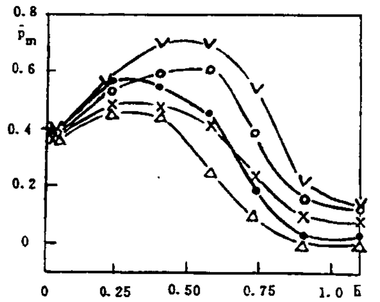


Fig. 5 3-D Seperation Model of Inlet Boundary Layers



• -Traditional ; Δ-Obtuse Zone; v-Acute Zone; o-Positively Curved; x-Negatively Curved

Fig. 6 Variations of Static Pessure Coefficient Averaged by Pitch along Axial Direction

transverse pressure gradient, being large, is almost not affected by the leaning or curving of blades. Therefore, it become the key factor to produce the passage vortices of high intensity. The other factors only affect the intensity, scale and position of passage vortices. The static pressure distribution along the blade height, although is the second role for the scale and intensity is the first one for the location of the passage vortices in the direction of the blade height. In traditional cascades the static pressure distribution along blade height is derived by passage vortices. The static pressure gradient from endwalls to the core of vortices is negative, and from the core to midspan of blades is positive as shown in Fig. 4. 1. In curved blade cascades there is another static pressure gradinent along blade height produced by the blade force component along blade height, except the one by the passage vortices. Positively curved blades produce a negatively pressure gradient starting from both endwalls, i. e, shape "C" static pressure distribution along blade height, while negatively curved blades a positive one, i. e, opposite shape "C" static pressure distribution. In both curved blade cascades the static pressure gradient is the summation of the one from passage vortices and the other from blade force components along blade height (Fig. 4. 1). Experimental results indicate that the static pressure gradient produced by the blade force has a considerable effect on the origination and development of passage vortices, and shape "C" static pressure distribution favors the passage vortices, while oppisite shape "C" one hinders them.

Compared with that of traditional cascade in the same measurement plane, the intensity of horseshoe vortices in the acute angle zones of lean blade cascade and positively curved blade cascade is more intensive. Besides, there is a negative pressure gradiet starting from the endwall and a shape "C" static pressure distribution. So the passage vortices in those two cases are formed in the more upstream plane and have higher intensity and larger scale in the same measurement plane, and locate nearer the midspan and pressure side. The passage vortices in the obtuse angle zones and negatively curved blade cascade are the opposite cases. From measurement plane 5 to 8 in Fig. 4, one finds that the passage vortices, in the acute angle zone and positively curved blade cascade have formed in plane 5; in traditional cascade in plane 6; and in obtuse angle zones and negatively curved blade cascade in plane 7. Moreover, for the two latter cases the passage vortices are weaker, nearer the endwalls, so produce smaller losses.

From the plane in which the passage vertices are formed to the blade outlet edge plane it is a process that the passage vortices develop towards the cascade middle and pressure side. Passage vortices, as centralized ones, are the only form to accumulate large kinetic energy in a narrow space, and their energy is provided by average flows. In turn, they have an intensive affect on the average flows. In cascades with high turning angle, most part of mass, mimentum and energy is transported by passage vortices. The low energy airflow in new boundary layers is transported to suction surface corner by the transverse pressure gradient, and then is entrained along suction surface by passage vortices; meanwhile on the pressure surface high energy airflows are convected from midspan to endwalls, reducing the flow losses near endwalls greatly. By convection passage vortices roll up the most part of low energy airflow in the passage increasing in the intersity and scale themselves.

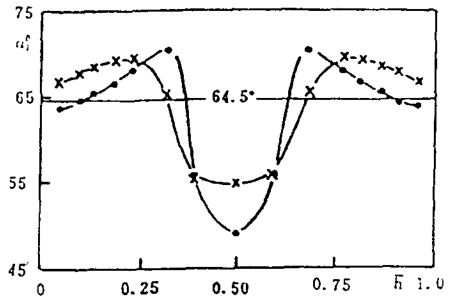
With passage vortices moving towards the middle of cascades, the upper and lower passage vortices with the same intersity and the opposite rotation directions approch each other and meet in the midspan at last, which happens earliest in positively curved blade cascade. When the two vortices meet, due to the strong interaction each other between them a transverse flow with high velocity in the pitch direction is produced in the meeting plane, which usually leads to the breaking of the vorices and dissapating of their energy. So the losses in the midspan suddenly increase and a big zone of high losses appears. Fig. 4 showes the upper and lower passeage vortices of positively curved blades have completely met in measurement plane 9, and the loss peak in the midspan reach up to 86.5%. The two vortices of traditional cascade start meeting in plane 9. As for lean blade cascade, the static pressure in acute angle zones, higher than that in obtuse angle zones, not only favors the passage vortices in acute angle zones and hinders them in the other zones, but also move the passage vortices in the acute angle zone to the obtuse angle zone (Fig. 4,e, measurement plane 6-9). In plane 9 the two vortices meet at 31% blade height and a loss peak of 56% appears. For negatively curved blade cascade the upper and lower vortices, being controlled in their corresponding zones by the opposite shape "C" static pressure distributuion, are still 0.38 blade height awary from each other in measurement plane 9.

Flows in Downstream

The experimental results from measurement plane 10 (in Fig. 4) show that in traditional cascade the complete meeting of passage vortices at the midspan dominates the whole outlet flowfield, and high loss area occupied the large part of the cascade middle with a loss core in the center of the passage. The loss core corresponds to the low pressure area and the lowest turning angle of airflows. In lean blade cascade the loss peak from the meeting is dissapated by mixing, which results in lossvalue decreasing and high loss area expanding and loss peak position moving up to 35% blade height. In negatively curved blade cascade the two vortices have not completely met in plane 10. The distance between the two vortex cores is 0.2 blade height. Compared with those of traditional cascade, the wake and high loss area reduce enormously, the loss values in these areas also are lower. In positively curved blade cascade the loss peak the in midspan goes down to 57% because of the dissapating of the vortex energy, the high loss area and loss value are obviously greater than those of traditional cascade. The growth of downstream loss is due to mixing caused by flow non-uniformity. A non-uniform flow will generally contain primary velocity in wake and secondary velocities in vortces. Both will contribute to mixing loss but the latter to be much more serious since it is reasonable to assume that all of the secandary kinetic energy is lost (Moore and Adhye, 1985). For a large turning angle cascade the mixing loss mainly depends on the intensity, scale of upper and lower passage vortex and distance between their cores. The greater the intensity and scale, the smaller the distance, the greater the mixing loss. The mass flux-averaged total loss coefficients of traditional, lean, positively curved and negatively curved blade cascade are 0.1948, 0.1883, 0.2256 and 0.1572, respectively, which indicates the losses of lean blade cascade are almost equal to those of traditional one, so using lean blades in rectangular cascades does not reduce losses, sometimes even increase them. Negatively curved blade cascade reduces losses by 19.3% and positively curved blade one increases losses by 15.6%, of those of traditional one.

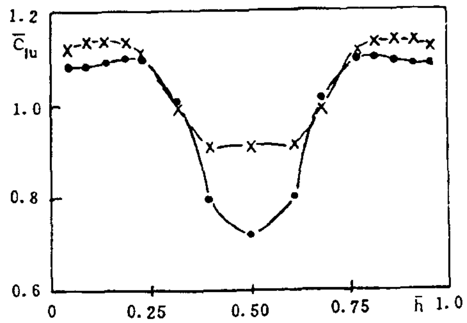
It can be derived by reviewing the whole flow field that the origination and development of horseshoe vortices and passage vortices take a predominant role in the flow field of traditional cascade, especially the meeting of upper and lower vortex in midspan results in high loses, airflow underturning and decreasing of work done ability; In lean blade cascade the improvement of exit flows in the acute angle zone does not result from the decrease of secondary flow losses produced in the zone. On the contray the secondary flow losses in the acute angle zone are much far bigger than those in the obtuse angle zone, and fortunately, the acute angle zone losses are transported to the obtuse angle zone by passage vortices, which further reveal that passage vortices entrain most part of low energy airflows in the passage, where the passage vortex moves is a low pressure and high loss area. Analysing Fig. 4 in details one can find although the passage vortices core does not agree with the loss peak and the lowest pressure point exactly, they are rather close to each others. The passage vortices have the intensive three-dimensional nature. Their vorticities can be divided into two components: the spanwise and streamwise vorticities. The spanwise vorticities equal to the circulations around blades decide the aerodynamic loads of blades. The greater are the streamwise vorticities produced secondary flows, the greater is the total loss of a cascade. The so called controlling the vortices means the controlling the streamwise vorticities and keeping the spanwise vorticities, which makes the total loss of the cascade reduce to the minimum under the condition of higher aerodynamic loads of blades. From the mention above we propose that in cascades with low aspect ratio and high turning angle the secondary vortical losses take the main part of the total losses. So the key to reduce the losses in this kind of cascades is to control the origination and development of horseshoe and passage vortices, especially to avoid the meeting of the passage ones. The obtuse angle zone hinders the two kinds of vortices efficiently, so using negatively curved blades (the dihedral between pressure surface and both endwalls are obtuse) is the logical development of using leaned blades. Negatively curved blades introduce the improvement in obuse angle zones to the same cascade.

Using negatively curved blades not only raises the cascade efficiency, but also makes the outlet airflow angles approach to the geometry ones, increasing the work done ability of airflows. From Fig. 7 one sees in traditional cascade the meeting of the two passage vortices produces a 16.5° biggest underturning angle in midspan, and approximate 6° overturning angles at 30% and 40% of relative blade height respectively. Negatively curving of blades reduces the biggest underturning angle by about 7°, and move the position of biggest overturning angle (2° smaller than that of traditional cascade) to endwalls. Experiment data indicates the averaged outlet angle along blade height is 1.5 degrees bigger than that of traditional cascade, which means negatively curving of blades not only decreases the secondary vortical losses, but also slightly raise the aerodynamic loading of the blades. According to Euler equations the outlet tangential velocity of rectangular cascades, C_{1u}, represents the work done ability of airflows. The variation of outlet tangential velocity along blade height in negatively curved blade cascade is similar to that in traditional cascade (Fog. 8). For traditional cascade



• -Traditional; x-Negatively Curved

Fig. 7 Distribution of Outlet Airflow Angle along Blade Height



• -Traditional; x-Negatively Curved

Fig. 8 Distribution of Outlet Tangential Velocity Coefficient along Blade Height th lowest work done ability point loactes at midspan from which the work done ability grows sharply in both directions to the endwalls, and almost holds constant from both 0. 25 and 0. 75 blade height to corresponding endwalls respectively. For negatively curved blade cascade the work done ability in the zone from 0. 31 to 0. 69 of blade height are raised enormously, resulting from the avoidence of the meeting of passage vortices. In the zone near endwalls the overturning of airflows increase the work done ability too. In the other zone the work done abilitys of traditional and negativly curved blade cascade are approximate equal. An obviouse conclusion is negatively curved blades increas work done ability of airflows greatly.

4. CONCLUSIONS

(1)In cascades with low-aspect ratio and high-turning angle, the secondary vortical losses from horseshoe and passage vortices take the main part of the total losses. The key to reduce the losses, therefore to improve the aerodynamic performance, of the cascades is to control the origination and development of horseshoe and passage vortices, especially to avoid the meeting of the passage vortices.

(2)The leaning of blades intensifies the passage vortices in the acute angle zones, and move them to the obtuse angle zones, at the same time controls those in the obtuse angle zones, which leads to the meeting position of both angle zone passage vortices locate in the obtuse angle zones. the lower energy airflows produced in the acute angle zones are entrained by this zone passage vortices and move to the obtuse angle zones, as a result the aerodynamic performance is degrated in the obtuse angle zone and improved in the acute angle zone.

(3)Use of negatively curved blade can control the origination and development of horseshoe vortices and passage vortices and confine the upper and lower passage vortices in their own sides, avoiding their meeting. Therefore, the secondary vortical losses of cascade are greatly reduced, and the efficiency is raised.

(4)As both the biggest underturning and overturning of airflows are caused by passage vortices, conrolling hte origination and development of passage vortices can redistribute the outlet airflow angle along blade height, and decrease the incidence on the next blade row, and intensify the work done ability by slightly increasing the load of blades.

REFERENCE

Harrison. S. , 1990, “Secondary Loss Generation in a Linear Cascade of High-Turning Turbine Blades”, Trans. ASME, J. of Turbomachinery, Vol. 112, pp. 618-624.

Han Wanjin, et al. , 1990, “The fluence of Blade Curving on End Seconsary Flow at Different Incidence”, Journal of Engineering Thermophysics, Vol. 11, No. 3. (in Chinese)

Ishii, et al. , 1986, “A Three-Dimensional Turbulent Detached Flow with a Horseshoe Vorex”, Trans. ASME, J. of Eng. for Gas Turbines and Power, Vol. 108, pp. 125-130.

Langston, L. S. , et al, 1977, “Three-Dimensional Flow within a Turbine Cascade Passage”, Trans. ASME, J. Eng. for Power, pp. 21-28.

Moore, J. and Adhye, R. Y. , 1985, “Secondary Flows and Losses Downstream of a Turbine Cascade”, Trans. ASME, J. Eng. for Gas Turbines and Power, Vol. 107, pp. 961-968.

Sieverding, C. H. , 1985,“Recent Progress in the Understanding of Basic Aspects of Secondary Flows in Turbine Blade Passages”, Trans. ASME, J. Eng. for Gas Turbines and Power, Vol. 107, pp. 248-257.

Wang Zhongqi. , et al, “The Effect of Balde Leaning on Cascade Aerodynamic Characteristics and the Experimental Study of Mechanism of Reducing Secondary Flow Losses by Leaned Blade”, Journal of Engineering Thermophysics, Vol. 9, No. 2. (in chinese)