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The Blade Curving Effects in a Turbine Stator Cascades With Low Aspect Ratio[1]

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Abstract: In a low speed plane cascade tunnel, the experiments for the cascades equipped with conventional straight blades, linear inclined blades and curvilinear blades were carried out. Through the comparisons of the experimental results, the improving effects of blade curving on the flow fields are discussed. The experimental results show that using curvilinear blades in the rectangular turbine stator cascades with low aspect ratio can reduce the overall flow loss by 30-40%.

1. Introduction

Almost twenty years ago, combined aerodynamically formed curvilinear blades are proposed. Since then mounting numerical and experimental data indicate that the use of curvilinear blades in turbine cascades decreases secondary flow loss both in design and in changed working environment [1-3]. Experiments conducted by these authors are mainly on the whole machine. Experiments on the whole machine can render realistic results, but they cost more and take longer and it is not possible to conduct multi-plan research. Furthermore, due to constraints of measurement conditions, measurement inside the duct cannot be obtained. Ref [4] has explored the effect on exit flow field of low aspect ratio rectangular turbine stator cascades due to blade inclination and revealed the mechanism for reducing secondary flow loss at the acute angle end. It further conjectures that by using curved vanes, both ends of which on the pressure side form an acute angle with the side walls, one can create a static pressure gradient distribution, positive at the top and negative at the bottom along the vane height. Thus the benefit of the acute angle inclination is introduced on both sides of the vanes. However, up till now, no experimental data are available to confirm the above conjecture.

[1]Supported by National Natural Science Foundation. This article was presented at the Heat Engine Aerodynamics and Thermodynamics Conference of the Assciation of Engineering Thermophysics in Beijing, November 1989.

This paper presents detailed measurements of the exit flow field and the surface static pressure distribution of cascades with linear, linea: inclined and curvilinear blades. It studies the effect on distribution of aerodynamic parameters along the vane height due to blade curvature. It analyzes problems including the selection of the inclination angle at the side wall of the curved blades, blade load, flow angle, and circulation variation. It provides a basis for applying curved blades in high pressure turbine stages, and in particular, in adjustment stages.

2. Experimental model

Experiments are conducted in a low speed wind tunnel with planar cascades. Rectangular turbine stator cascades consisting of seven types of blades are tested. These include: No. 1, corresponding to straight blades (Fig. 1, a), No. 2, No. 3, and No. 4 corresponding to linear inclined blades with inclination angles 10°, 20°, and 30° (Fig. 1, b), No. 5, No. 6, and No. 7 corresponding to curved blades with 10°, 20°, and 30° inclined angles at the side walls. Stacking curves are shown in Fig. 1, d. The best blade shape is still the one which remains parallel to the plane of the side walls while the blade is inclining or curving. Five hole bundle type measuring pins are used to measure the variations, along the gap and along the vane height, of the total pressure, static pressure and flow direction of seven types of cascades at zero angle of attack. There are seven measuring stations along

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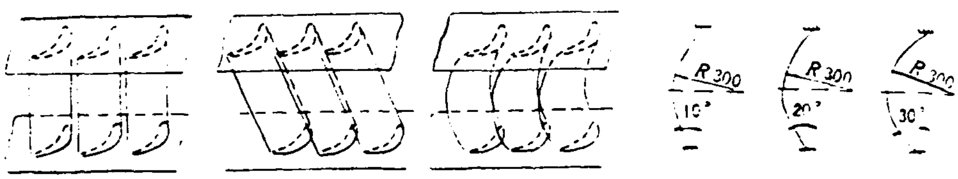


Fig.1 here

(a) straight blade cascades (b)linear inclined blade cascades (c) curvilinear blade cascades (d)curved blade stacking curve shape.

Fig. 1 Rectangular turbine cascades

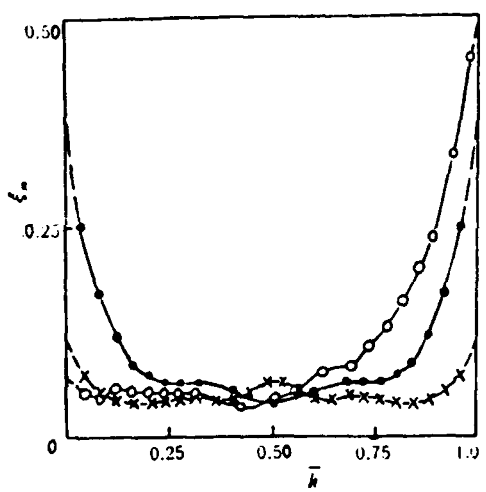
the the vane height on the blade surface. Each station has 30 static pressure measuring holes along the airfoil to measure static pressure

a

distribution on the blade surface. Other geometric and aerodynamic parameters of the cascades are: chord length b = 73 mm, axial chord length B = 48.39 mm, relative gap distance t/b = 0.685, aspect ratio $\bar{s}$ = 0.68, geometric inlet angle α_0 = 90°, geometric exit angle α_{1P} = 19°, inlet total pressure P_0^* = 6570 Pa (surface pressure), Reynolds Number in the middle of the cascades Re = 4.35 × 10^5, and the inlet boundary layer thickness δ = 10mm.

3. Discussions of the experimental results

Fig. 2 shows that, in low aspect ratio straight cascades, the lateral secondary flow loss at the ends contributes a significant part to the total loss; it is approximately 60% under the conditions of this experiment.



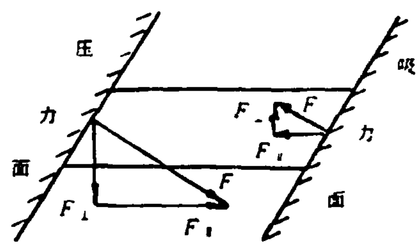


Fig. 3 here

Fig. 2 Distribution along the blade height of the gap average of the energy loss coefficient. i). straight blade, ii). linear inclined blade, iii). curved blade (s=20°).

Fig. 3 Blade force decomposition diagram. i) pressure side, ii) suction side.

Hence the potential for improving the efficiency of this type of cascades lies in reducing the secondary flow loss at the ends. When linear inclined blades are used, the energy loss coefficient on the acute angle end between the pressure surface and the side wall (the lower side of the blade) is greatly reduced; at the same time, the energy loss coefficient on the obtuse angle side between the pressure surface and the side wall (the upper side of the blade) increases rapidly. Usually, the increase of the loss on the obtuse angle side surpasses the decrease of the loss on the acute angle side. Therefore, the use of linear inclined blades in rectangular cascades will not reduce the loss. On the contrary, it increases the loss. Nevertheless, experimental results from linear inclined blades inspire us to think that loss at both ends of the blades may be reduced simultaneously if curved blades which form acute angles between the pressure side and two side walls are used. Experimental result in Fig. 2 shows that blade curving indeed reduces lateral secondary flow loss. Although the loss in the center of the blade increases slightly, the reduction of the loss at both ends is significantly greater than the increase in the center. For curved blades with 10°, 20°, and 30° inclination angle at the ends, energy loss coefficient is reduced 32.3%, 41.1% and 35.4% respectively, from that of straight blades.

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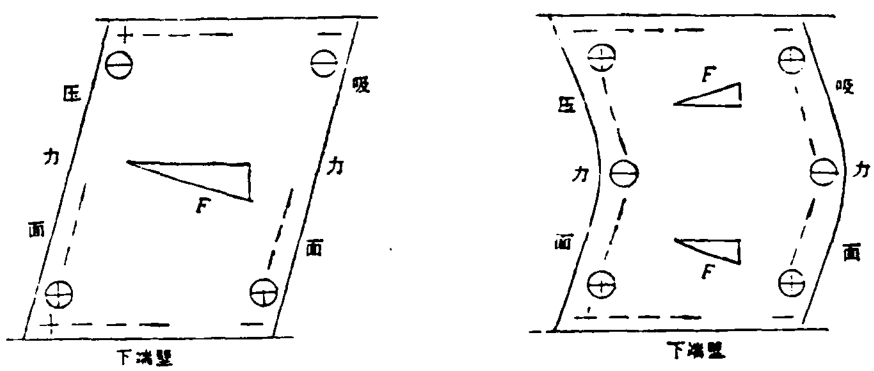


(a) (b)

Fig. 4 Schematic diagram of pressure gradient formation along blade height. +, - indicate static pressure field formed by horizontal force component, arrow points to lower pressure from higher pressure. ⊕, ⊖ indicate static pressure field formed by vertical force component, the directions of arrows are the same. i). upper side wall, ii). lower side wall, iii) pressure side, iv) suction side.

Another phenomenon shown in Fig. 2 is that the loss coefficient near the acute angle end of the side wall and in the middle of the blade for linear inclined blade is always smaller than that of the curved blade at the corresponding positions. This difference can be explained by the static pressure distribution along the blade height. In a linear inclined blade flow channel, the reaction forces on the flow by the pressure surface and the suction surface of the blade are perpendicular to the respective surfaces (ignoring viscous force effect). Both of these two reaction forces can be decomposed as a horizontal force and a vertical force. These two pairs of forces are opposite in direction, and the magnitude of pressure side is greater than that of the suction side (Fig. 3). Hence, the flow is subjected to a horizontal force component pointing to the suction surface and a vertical force component pointing downward (Fig. 4, a). The horizontal force component which forms lateral pressure gradient in the channel balances with the centrifugal inertia force cause by air flowing through the channel. Similarly, balanced by vertical force component, a negative pressure gradient along the blade height is formed (Fig. 5). In cascades of curved blades which are symmetric up and down, the upper and lower forces are equal in magnitude but opposite in direction, each forms an angle ε with one side of the side wall. Therefore, the two vertical components of them are equal in magnitude and opposite in directions, each pointing towards the top side of the side wall. Balancing with these two force components, a static pressure distribution along the blade height is formed, which is a positive gradient at the blade top, and a negative gradient at the blade bottom. Static pressure measurement on the blade surface confirms the above analysis (Fig. 5). From this we infer that the negative pressure gradient along blade height of the former may be more beneficial than the latter for sucking the boundary layer of the lower part of the blade near the side wall into the main flow region; in curved blade cascades, the positive pressure gradient at the blade top and the negative pressure gradient near the blade bottom both drive the boundary layer at the two ends into the middle so the energy loss there sees some increase.

Fig. 6 further illustrates transport situation of the boundary layer. In a straight blade, high loss regions are located at the two ends. At the height 30% from the side wall, local high loss region corresponds to the vortex center of the passage. In a linear inclined blade, high loss region is concentrated at the end of acute angle. In curvilinear blade cascades, as the curving angle increases, the high loss region near the side walls may even disappear; in the mean time, high loss region is shifted to the center of the blade and widens in the direction of the gap.

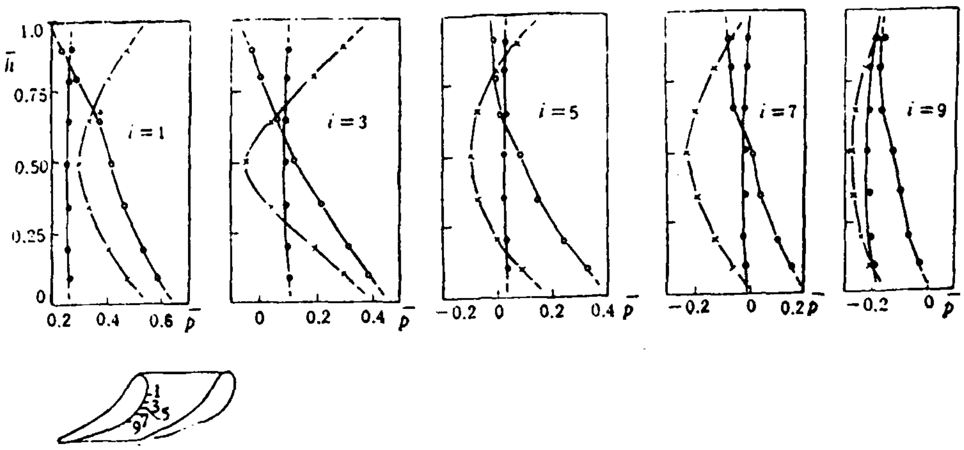
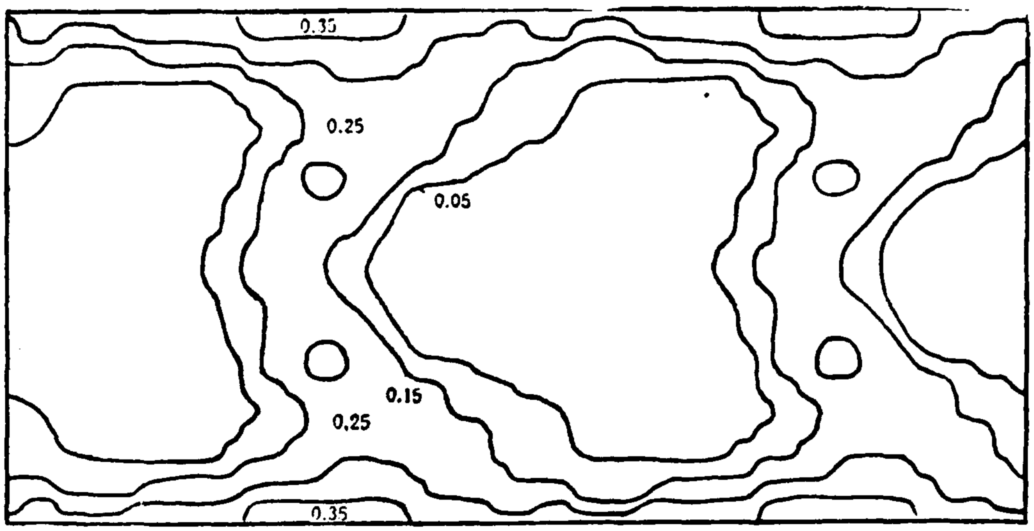


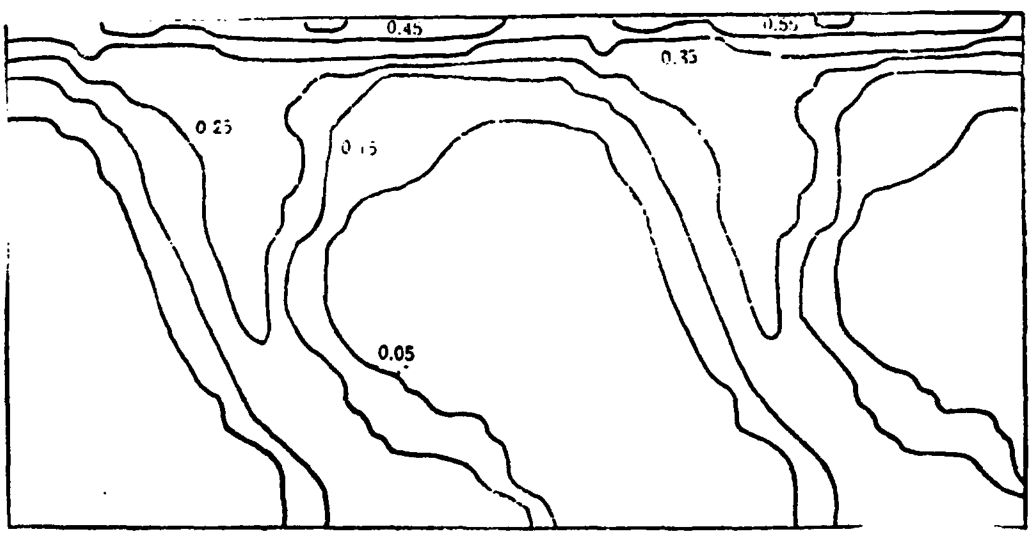
Fig. 5 Distribution along the blade height of static pressure coefficient of blade surface. i) straight blade, ii) inclined blade, iii) curved blade.

There exists an optimum inclination angle in the acute angle end of a linear inclined blade[4]. Experimental data indicate that, under the experimental conditions of this paper, the best inclination angle at the acute angle end is approximately 25°. Meanwhile, there also exists an optimum inclination angle corresponding to the minimum cascade total loss in a curved blade; it is in the neighborhood of 20°. This indicates that, compared with the corresponding linear inclined blade, the optimum inclination angle of a curved blade is decreased by some amount. If the inclination angle is greater that the optimum inclination angle, the rate of loss decrease at the ends will be lower that the rate of loss increase in the middle, resulting an increase of cascade total loss. The optimum inclination angle depends on the cascade aspect ratio, flow angle of attack, turning angle and the inlet boundary layer thickness, and the degree of turbulence. For different cascades, it is to be determined through experiments.

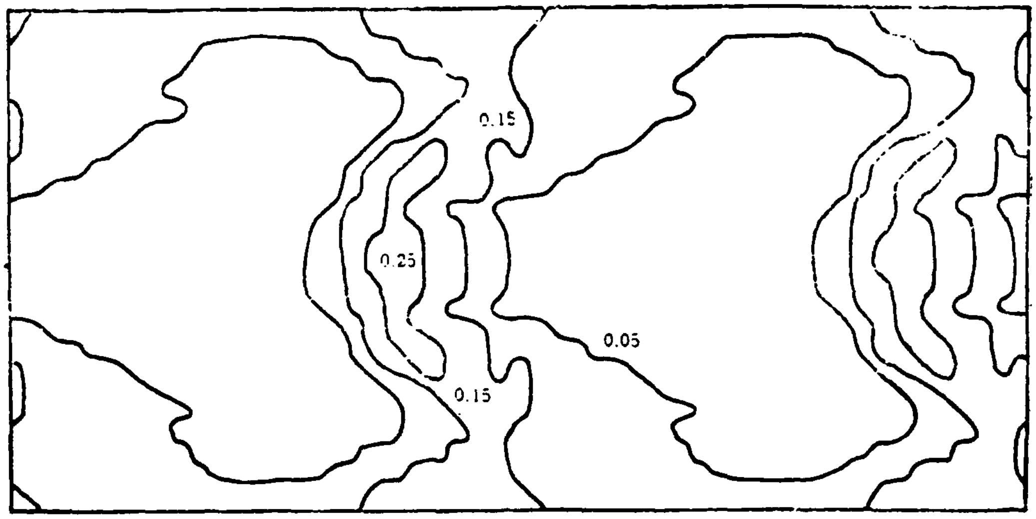
In a straight blade, the surface static pressure is distributed almost evenly along the blade height. The blade load along the blade height is also nearly uniform, except in the boundary layer near the side walls where blade force loss occurs. The inclination and curvature of the blade change the surface static pressure distribution of the blade; consequently the blade load is changed. Compared with the straight blade, in a linear inclined blade, the load at the acute angle end decreases while the load at the obtuse angle end increases (Fig. 8). In a curved blade, in the region which is 15% of height from the side walls, the blade load decreases because the pressure increase on the suction side is greater than that on the pressure side. It thus can be inferred that the lateral pressure gradient



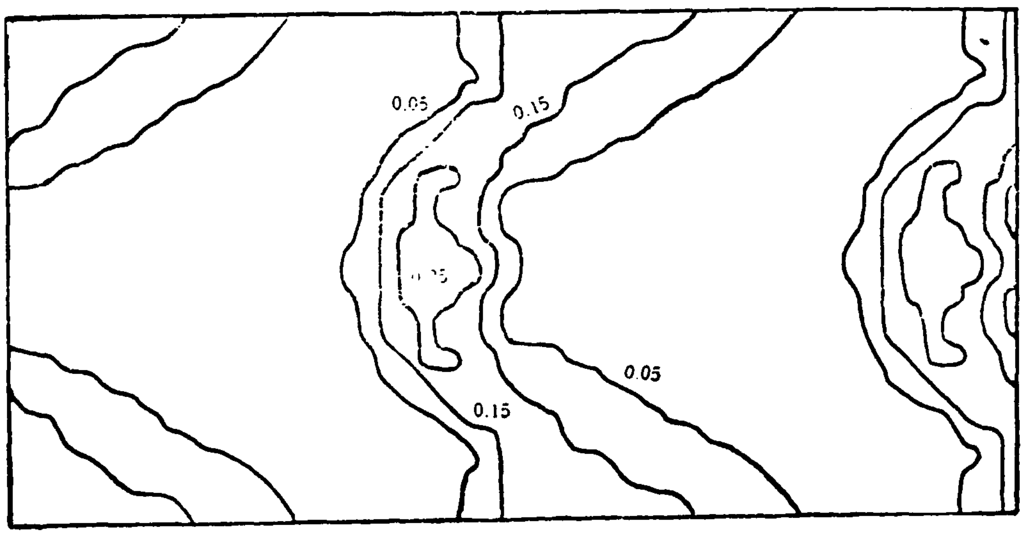
a. straight blade.



b. inclined blade (ε = 20°)



c. curved blade (ε = 10°)



d. curved blade (ε = 20°)

Fig. 6 Distribution of curves of equal energy loss coefficient

on the side walls will definitely decrease, which is another reason why curved blades can reduce the secondary flow on the side walls. In the region which is located greater than 15% on the blade height, blade load in the front half of the flow channel decreases and the blade load in the rear half of the flow channel increases. The closer to the center of the blade, the longer the portion of the increased load in the flow channel. Therefore, the aerodynamic load of a curved blade along the entire blade height may be slightly lower than that of a straight blade.

In a straight blade, the maximum flow angle (26.1°) and minimum flow angle (17.9°) both occur in a region 24% of the blade height from the side wall. For flow to enter into moving vane duct without impact, the torsion of the moving vanes must be very severe (Fig. 9). In short vane stages, the moving vanes are usually designed according to the aerodynamic parameters of the medium diameter, hence large angle of attack occurs at both ends of the moving vanes. This not only causes impact loss but also expands regions of high fluctuation in the moving vane ducts. For linear inclined blades, the flow angle is larger at the acute angle end and smaller in the obtuse angle end. The flow angle is even less uniform along the entire blade height. If the objective is to provide good inlet condition for the moving vanes, linear inclined blades cannot be used (Fig. 9). In curved blade cascades, as the inclination angle at the ends increases, the maximum flow angle decreases and the place it occurs moves to the ends; the minimum flow angle also increases. Consequently, flow angle along the entire blade height is closer to the cascade geometric exit angle (19°). This is beneficial both to the moving vane design and to the rebuilding of turbines not designed according to a controlled vortex.

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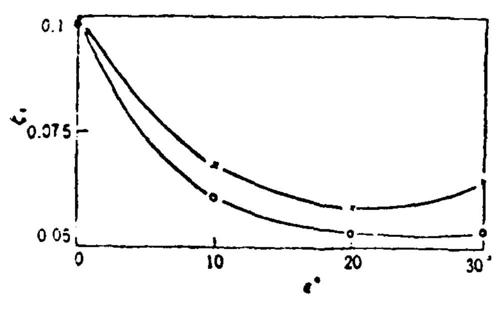

Fig. 7 Variation of total loss coefficient as a function of inclination angle. i) linear inclined blade, ii) curved blade.

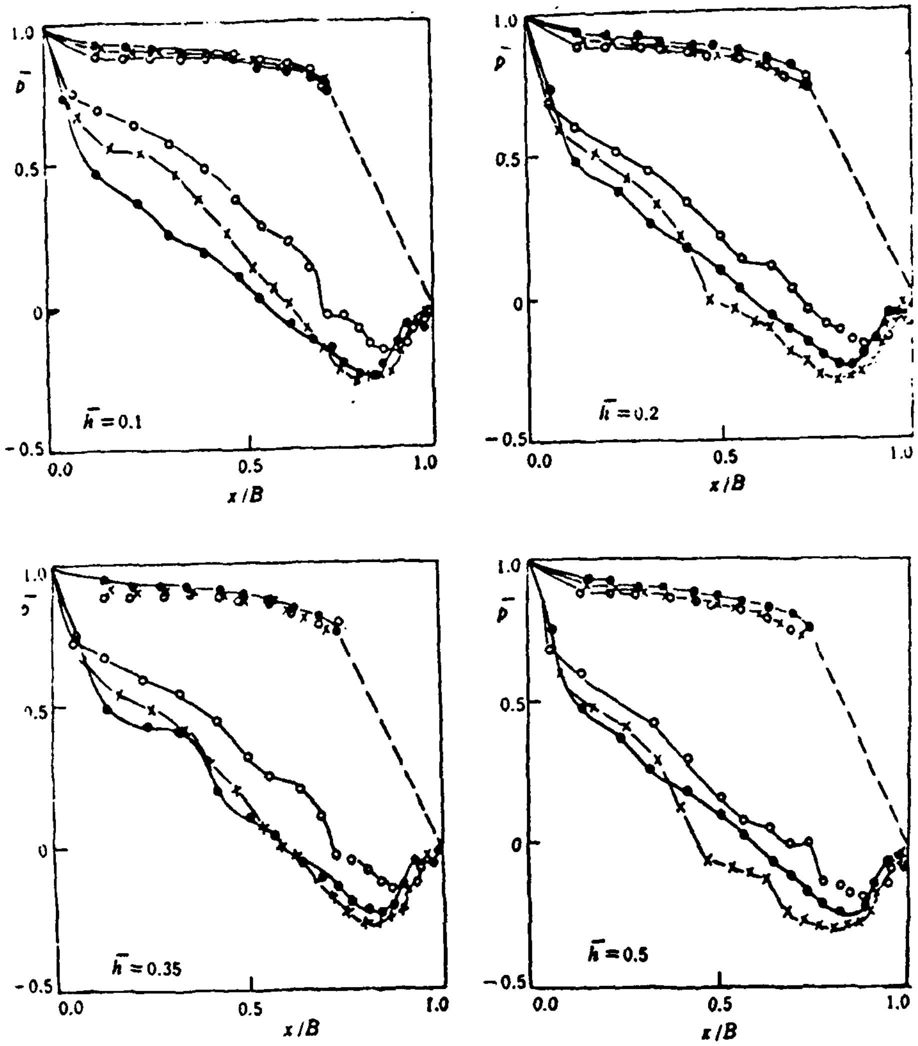

Fig. 8 Distribution of the static pressure coefficient along the blade airfoil. i) straight blade, ii) linear inclined blade, iii) curved blade.

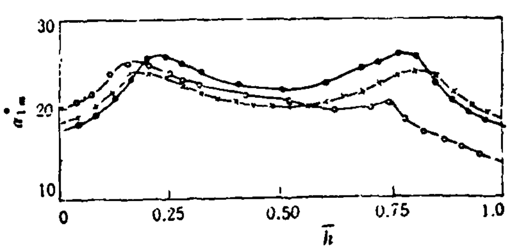

Fig. 9 Distribution of flow angle gap average along the blade height. i) Straight blade, ii) linear inclined blade, iii) curved blade.

From Euler's equation, $h_u = u(C_{1u} - C_{2u})$, the magnitude of C_{1u} indicates the ability of the flow to do work. According to Fig. 10, for straight blades, flow's ability to do work is the least near the side walls. Near the center of the blade, the flow's ability to do work is the largest. Compared with straight blades, for linear inclined blades, the flow's ability to do work is improved near the acute angle end but deteriorates noticeably near the obtuse angle end. For curved blades, since the boundary layer near the side walls are sucked to the main flow, flows there are sped up. Thus, the flow's ability to do work is improved significantly. Though the flow speed near the center of the blade is reduced slightly, the flow angle is smaller than that of the straight blade. Hence the flow's ability to do work is also slightly improved. As a result, the flow's ability to do work is improved along the entire blade height. In curved blade cascades with optimum inclination angle at the side walls, the flow's ability to do work is nearly the same along the entire blade height.

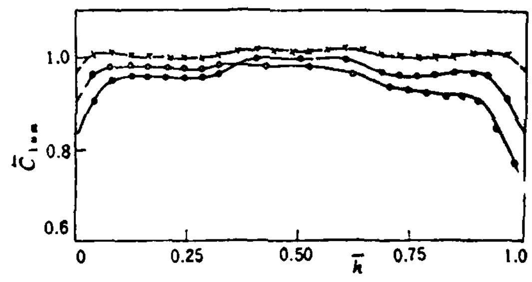

Fig. 10 Distribution along the blade height of the tangential velocity coefficient averaged along the gap.

4. Conclusion

1. In low aspect ratio turbine stator cascades, the use of curved blades can create a static pressure distribution along the blade height, which is a positive pressure gradient at the blade top and a negative pressure gradient at the blade bottom. Under the action of this static pressure distribution, the boundary layer near the two ends is sucked to the main flow. Hence the secondary flow loss at the ends is reduced and the distribution of energy loss coefficient along the blade height is almost uniform. Compared with straight blades, the loss coefficient can be reduced by nearly 30-40%.

2. The inclination angle at the two side walls of curved blades has an optimum value. It is smaller than the optimum angle at the acute angle end of the corresponding linear inclined blades. It is also dependent on the aspect ratio of the cascades, flow angle of attack, turning angle and inlet boundary layer thickness, degree of turbulence, and other factors.

3. Use of curved blades can increase the minimum flow angle of straight blades, reduce the maximum flow angle, and cause the flow angle along the entire blade height to approach more closely the geometric exit angle of the cascades. This is beneficial both to the moving vane design and to the rebuilding of turbines not designed with a controlled vortex.

4. Use of curved blades can reduce the aerodynamic load of the blades at the two ends. Hence the lateral pressure gradient near the side walls is reduced. This is advantageous in reducing secondary flow at the side walls. Though the aerodynamic load of curved blades is lower than that of the straight blades, the flow's ability to do work is significantly improved.

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