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Control of the boundary layer on compressor blade suction surfaces with the momentum jet

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Keywords: compressor; cascade; boundary layer; flow control; jet

Abstract
The boundary layer thickness on a compressor blade suction surface increases rapidly under a adverse pressure gradient and even separates from the blade surface. This paper proposes a novel method for developing the slot inside the blade, with the inlet of the slot located at the leading edge of the blade and the outlet located at the suction surface, using the momentum of the incoming flow to form a high velocity jet to control the boundary layer on the suction surface. For a plane cascade with a diffusion factor of 0.45, the effects of the main slot parametres (such as the shape of the slot and the positions of the slot inlet and outlet) on the flow in the slot, the flow field and the aerodynamic performance of the cascade were investigated with a numerical method. When the aerodynamic performance of cascades with slotted and unslotted blades was compared, it was found that a reasonable slot structure can effectively inhibit the development of the boundary layer on the blade suction surface and greatly improve the aerodynamic performance of the cascade. Based on the influence of the slot parametres of the above cascade, the slot of a plane cascade with a diffusion factor of 0.60 was designed. The numerical calculation results show that the slotted cascade with a diffusion factor of 0.60 outperformed the slotted cascade with a diffusion factor of 0.45. This result showed that the higher the cascade load, the greater the performance improvement from slotting. Furthermore, the unslotted and slotted cascades were tested, and the test results agreed well with the calculations. The aerodynamic performance of the slotted cascade was better than that of the unslotted cascade, which verifies the accuracy of the calculation method and the feasibility of blade slotting for suppressing the development of boundary layers on suction surfaces and reducing flow loss.

Nomenclature

d_1	axial distance between the inlet centre point of the slot and the leading edge point
d_2	axial distance between the outlet centre point of the slot and the leading edge point
d_3	width of the slot inlet
d_4	width of the slot outlet
L_1	spline curve of slot
L_2	spline curve of slot
D	diffusion factor
W_1	the inlet velocity of a cascade
W_2	the outlet velocity of the cascade
P_1^*	the total pressure at the cascade inlet
P_2^*	the total pressure at the cascade outlet
P_1	the static pressure at the cascade inlet
i	attack angle
m_{slotr}	ratio of the flow rate in the slot to that in the cascade

X	relative axial position
Ma	mach number
SS	suction surface
PS	pressure surface
EXP	experimental data
Cal	calculating data

Greek symbol

τ	cascade solidity
ΔW_u	circumferential velocity difference between the inlet and the outlet
$\Delta\beta$	flow turning angle
β_1	inlet flow angle from the axial direction
β_2	outlet flow angle from the axial direction
$\overline{\omega}$	total pressure loss coefficient of a cascade
$\overline{\omega}_{slot}$	total pressure loss coefficient of a slot
$\overline{\omega}_{slotr}$	ratio of the total pressure loss of the slot to that of the cascade
δ_1	thickness of boundary layer

1.0 Introduction

In the late 1960s, Rockenbach proposed a slot inside a compressor blade and used the pressure difference between the pressure surface and the suction surface to form a suction surface jet to control the development of a boundary layer on the suction surface. Slots of various configurations were made in the rotor and stator blades of a single-stage axial compressor, and the experiments showed that the slot suppressed flow separation in the middle section of the blade but had no positive effect on corner flow control [1]. Experiments on slotted cascades showed that flow loss control was not only unsatisfactory but also had a negative effect (the loss increased) [2, 3].

Sturm et al. hypothesised that the low outlet speed of the slot was the cause and proposed using an external air source to form a jet to actively control the boundary layer on the blade suction surface, with the jet speed equivalent to the local mainstream speed and the jet direction as parallel to the mainstream direction as possible [4]. On the test bench of a four-stage low-speed axial compressor, Kirtley et al. redesigned the third-stage stator with ultralow solidity, and an external jet was used to control the boundary layers on the blade suction surfaces [5]. Nerger et al. used an external air source to generate jets on the suction surface and the endwall to control corner flow in a highly loaded low-speed cascade [6]. The experimental results showed that the method increased the static pressure rise of the cascade. If the air source energy input was not considered, the jets effectively reduced the flow loss; however, if the air source energy input was considered, it was difficult to reduce the flow loss.

To reduce the flow rate of the jet and thus reduce the energy input of the air source, Culley et al. used an unsteady jet to control the flow in the stator corner of a multistage low-speed axial compressor. The experimental results showed that better results were obtained by using an unsteady jet with the same flow rate as a steady jet [7]. Gmelin et al. obtained similar results on a highly loaded subsonic cascade with experiments and calculations [8]. Zander et al. showed that an unsteady jet can strengthen mixing of the boundary layer with the external potential flow and delay separation and blockage in the corner area based on cascade experiments [9].

Slotting between a blade pressure surface and the suction surface to form a jet on the suction surface is simple and does not require an external air source, but the resulting jet speed is usually low. Early research, which was limited by experimental and calculation technology levels, was not thorough enough, and satisfactory results were not obtained. An active control method was used, which involved using an external air source to generate steady/unsteady jets. This method can generate the required jet speed and flow rate while simultaneously generating jets on the blade suction and annular wall surfaces, with the jets closing when flow control is not required. However, this method requires an external air source, as well as a high-frequency air valve for unsteady jets.

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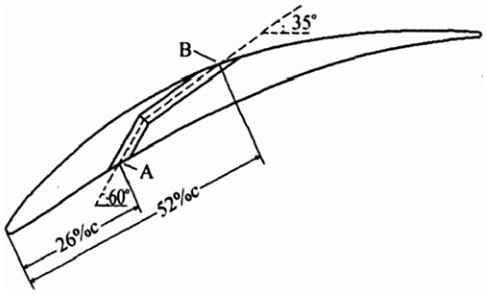

Figure 1. *Convergent turning slot of two-segments [12].*

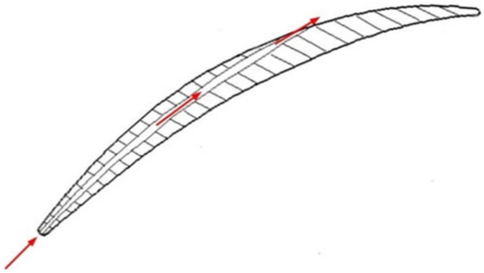

Figure 2. *Slot structure.*

Wang Rugen et al. proposed a convergent two-segment turning slot to reduce the difference between the outlet jet and main flow directions and increase the jet speed, thereby improving the jet effect (see Fig. 1). The numerical simulation results of a 2D cascade flow showed that the slot can reduce flow loss at a positive attack angle [10]. Slotting near the blade hub or tip can reduce the separation of the trailing edge of the blade suction surface and corner separation in a cascade flow [11]. Slotting near the stator blade hub in a single-stage compressor can effectively improve both compressor efficiency at the design point and the stall margin [12]. Slotting in highly loaded cascades can effectively suppress corner separation and flow loss [13, 14]. A vortex generator and slotting were combined and applied in a single-stage transonic compressor, and the numerical calculation results revealed that the combined control method eliminated the large-scale separation of the compressor and significantly improved aerodynamic efficiency and stability [15].

Lu Lipeng et al. proposed creating two slots at the compressor blade hub to form three segments with a wing-like shape, which can increase the slot flow rate and reduce the mixing loss of the jet with the main flow. For a highly loaded cascade, the experimental results showed that the two slots effectively suppressed open separation and improved the aerodynamic performance under multiple working conditions (especially at the positive attack angle). The control effect of two slots on the corner flow is better than that of one slot [16].

Slotting between the blade pressure surface and the suction surface can form a flow jet that controls the boundary layer on the suction surface, but the momentum of the jet is low. This paper proposes a new slotting method in which the momentum of the incoming flow was used to form a high-speed jet (see Fig. 2). The effects of the main slot parametres on the flow fields and aerodynamic performance of cascades with medium and high loads were investigated, and the aerodynamic performance of unslotted and slotted cascades were compared.

2.0 Analysis of the flow fields in a slotted cascade

The boundary layer on the suction surface of a compressor blade is thick, and as the attack angle increases, the thickness of the boundary layer increases, potentially causing flow separation. As shown

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Table 1. *Main parametres of the cascade*

Inlet Ma	τ	$\beta_1/(^\circ)$	$\beta_2/(^\circ)$	D
0.7 Ma	1.5	42	36	0.45

Table 2. *Key parametres of Slot 1*

d1/chord	d2/chord	d3/chord	d4/chord
0	60%	1%	0.5%

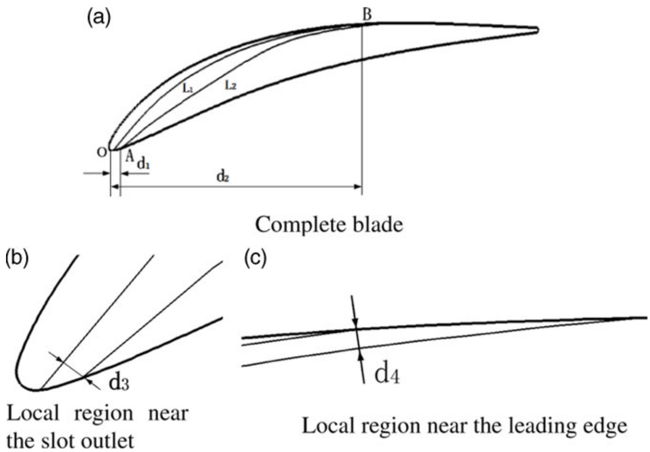

Figure 3. *Slot structure.*

in Fig. 3, this paper proposes a new slotting method in which the inlet of a slot is located at the leading edge of the blade and the outlet is located at the suction surface. The air enters the slot from the leading edge and is ejected from the suction surface. The momentum of the incoming flow is used to form a high-speed jet, effectively controlling the development of the boundary layer on the suction surface.

The key parametres that determine the geometry of the slot are as follows: the axial distance d1 between the inlet centre point of the slot (A) and the point O (the leading edge point of the blade), which determines position of the slot inlet at blade leading; the axial distance d2 between the outlet centre point of the slot (B) and the point O (the leading edge point of the blade), which determines position of the slot outlet, the width of the inlet d3 and the width of the outlet d4, which determine the flow rate in the slot; and the shapes of two sides of the slot, L1 and L2.

To investigate the possibility of improving the aerodynamic performance of compressor stators and the influence of key parametres on the flow field, a transonic compressor cascade with a design Mach number of 0.7 was selected; the main parametres of the cascade are shown in Table 1. The blades in the cascade were slotted, and the key parametres of the slot are shown in Table 2; this slot is denoted as Slot 1. The diffusion factor (D) is defined as follows:

$$D = 1 - \frac{W_2}{W_1} + \frac{\Delta W_u}{2\tau W_1} \tag{1}$$

In the formula, W_1 is the outlet velocity of the cascade, τ is cascade solidity, ΔW_u is circumferential velocity difference between the inlet and the outlet.

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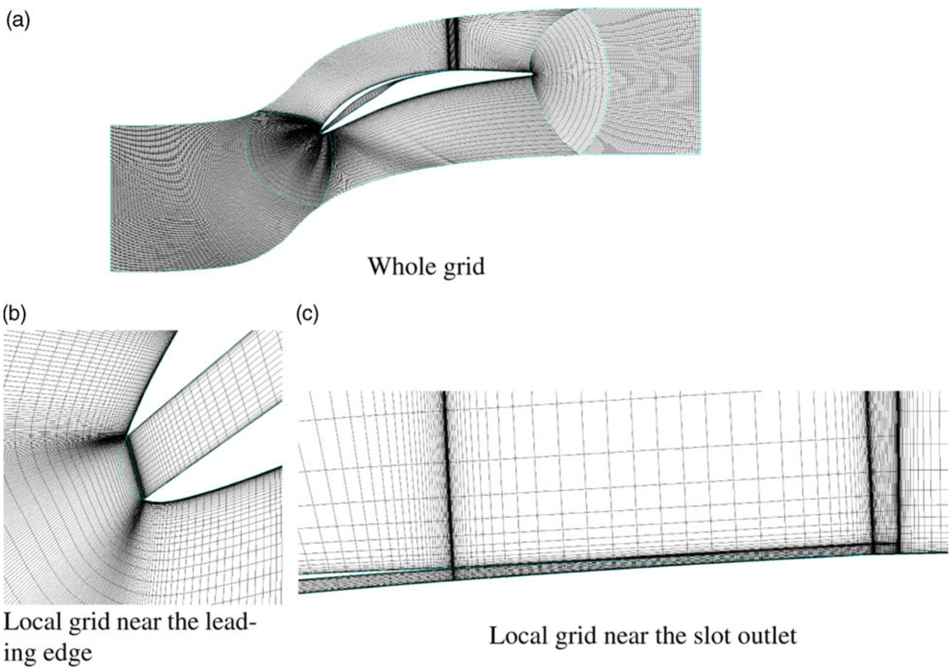

Figure 4. *Grid structure.*

The flow fields in the cascade were simulated using NUMECA software; the Spalart-Allmaras turbulence model was selected, and H-shaped structured meshes were generated by the Igg of the software. Given the small angle between the outlet of the slot and the suction surface in the slotted cascade, to ensure good grid orthogonality, two grid blocks near the outlet of the slot were added to the H-shaped structured meshes of the unslotted cascade, as shown in Fig. 4. The grid cell numbers of the unslotted and slotted cascades were 30,000 and 4,0000, respectively, and the grid cell number in the slot was 5,000, which will be validated in Section 4.

Flow turning angle ($\Delta\beta$) and total pressure loss coefficient ($\overline{\omega}$) are the performance parametres of cascade. Flow turning angle($\Delta\beta$) is defined as:

$$\Delta\beta = \beta_2 - \beta_1 \tag{2}$$

In the formula, β_1 is the inlet flow angle from the axial direction, β_2 is the outlet flow angle from the axial direction.

Total pressure loss coefficient ($\overline{\omega}$) is defined as:

$$\overline{\omega} = \frac{P_1^* - P_2^*}{P_1^* - P_1} \tag{3}$$

In the formula, P_1^* is the total pressure at the cascade inlet; P_2^* is the total pressure at the cascade outlet; P_1 is the static pressure at the cascade inlet.

The aerodynamic performance of the slotted cascade is shown in Fig. 5, and that of the corresponding unslotted cascade is shown in the same figure for comparison. As shown in Fig. 5, over the entire range of the attack angle, the flow loss in the slotted cascade was smaller than that of the unslotted cascade, and the flow turning angle of the slotted cascade was larger than that in the unslotted cascade; especially at the positive attack angle, as the angle increased, the thickness of the boundary layer on the suction surface increased, and the effect of the slot suppressing the boundary layer became more noticeable. Figure 6 shows that the slot can almost suppress the boundary layer.

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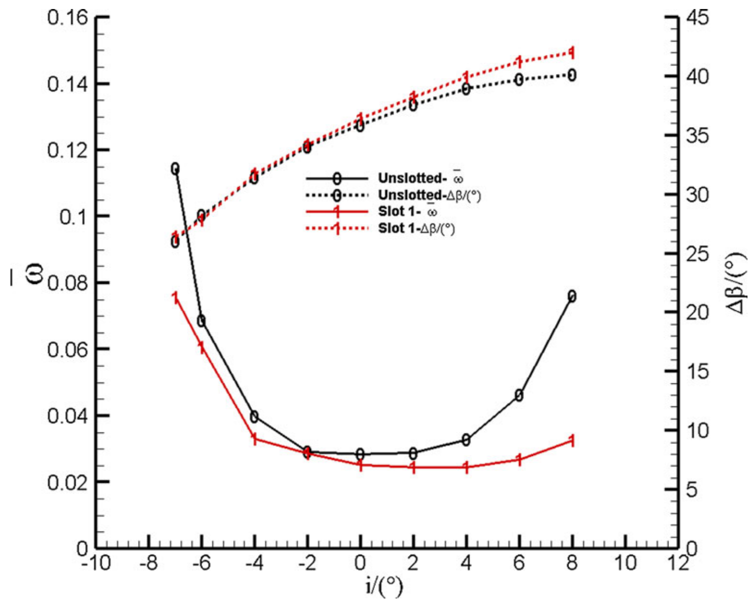

Figure 5. *Performance of the unslotted and slotted cascades.*

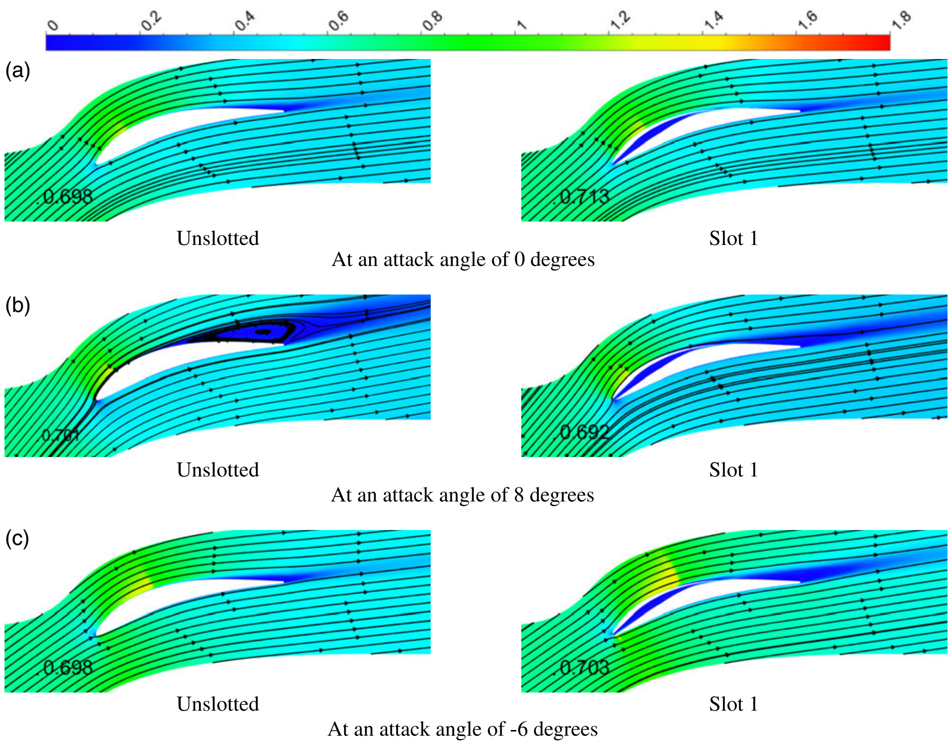

Figure 6. *Mach number contours.*

Table 3. *Aerodynamic parametres at an attack angle of 0 degrees*

Cascade	$\overline{\omega}$	$\Delta\beta/(°)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{slotr}/(\%)$	$m_{slotr}/(\%)$
Unslotted	0.0284	35.87	–	–	–
Slot 1	0.0253	36.40	0.1070	3.41	0.81

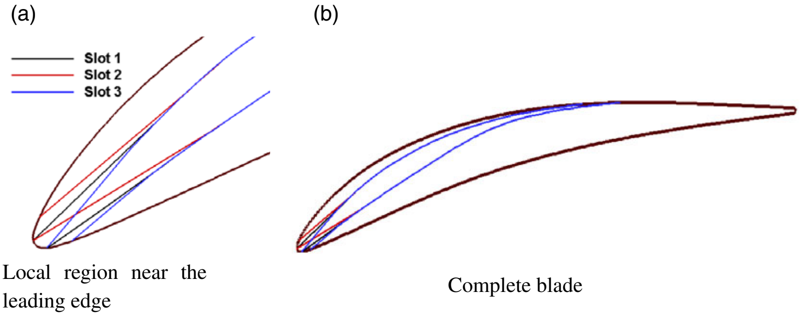

Figure 7. *Inlet locations of the slots.*

Table 3 shows that at an attack angle of 0 degrees, the total pressure loss coefficient in slot ($\overline{\omega}_{slot}$) was as high as 0.1070, and the flow loss in the slot was large due to wall friction. However, because the ratio of the flow rate in the slot to the total flow rate (m_{slotr}) was small (0.81%), the flow loss in the slot ($\overline{\omega}_{slotr}$) only accounted for 3.41% of the total loss.

Based on the above comparison of slotted and unslotted cascades, the overall effect of the slotting was described. Next, the effects of the key parametres of the slot on the slotted cascades were analysed to better understand the flow characteristics of slotted cascades.

3.0 Effects of the key parametres of the slot on the flow fields of the slotted cascade

3.1 Influence of the slot inlet location

The flow rate in the slot is affected by the location of the slot inlet at different attack angles, which affects the performance over the entire range of attack angles. The inlet location d1 of Slot 1 (see Table 2) was zero. The inlet location of Slot 1 was directly on the leading edge of the blade; the location was biased to the suction surface to obtain Slot 2 and biased to the pressure surface to obtain Slot 3. The inlet locations of the three slots are shown in Fig. 7.

The performance of the three cascades with different slot inlet locations is shown in Fig. 8. Figure 8 shows that when the slot inlet location is directly on the leading edge of the blade (Slot 1), the attack angle of the lowest loss is close to 0 degrees; when the slot inlet location is biased towards the suction surface (Slot 2), the attack angle of the lowest loss is negative (−4 degrees); and when the slot inlet location is biased towards the pressure surface (Slot 3), the attack angle of the lowest loss is positive (4 degrees). The figure also shows that flow losses in unslotted cascades are generally larger than those in cascades Slot 1 but lower than those in Slot 2 and Slot 3 cascades. This indicates that the slot inlet location is critical to the performance of the cascade. As shown in Fig. 9(a), at an attack angle of 0 degrees, there are local flow separations near the inlets of Slot 2 and Slot 3 that cause flow blockages in the slots, reduce the flow rate and increase the flow losses in the slots (see Table 4). Therefore, the total losses of the two cascades increase and the flow turning angle decreases (see Table 4). Similar analysis can be used for Fig. 9(b) and (c). When Fig. 9(a), (b), (c) and Table 4 are compared, it can be seen that: (1) when the slot inlet location is directly on the leading edge of the blade (Slot 1), the flow can easily enter the slot at different attack angles, and changing the attack angle has a relatively small effect on the flow rate and loss of the slot, with the lowest loss and largest flow rate at an attack angle of

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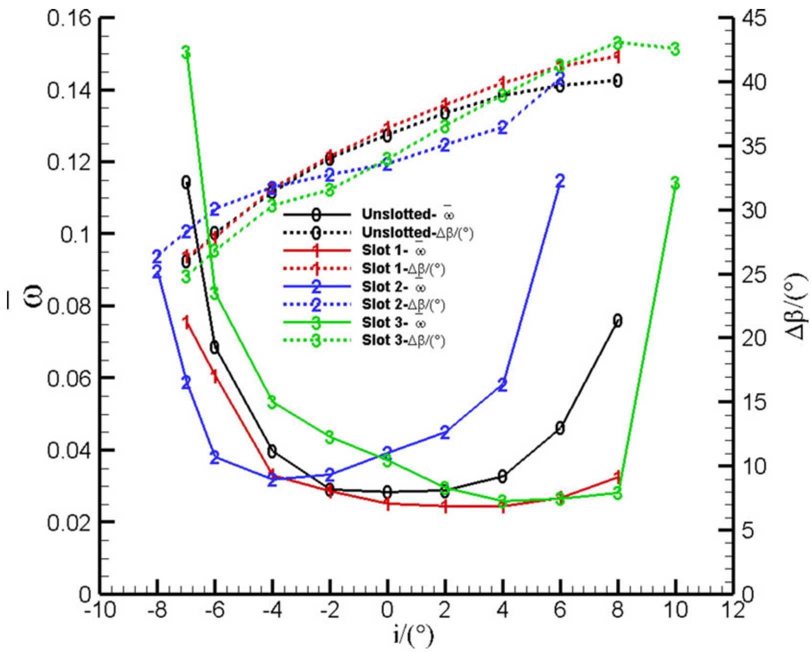

Figure 8. *Performance of cascades with different slot inlet locations.*

0 degrees; (2) when the inlet location is biased towards the suction surface (Slot 2), the sharp corners of the leading edge cause local flow separation near the slot inlet at an attack angle of -4 degrees, and as the attack angle increases, the separation region expands and the flow rate in the slot decreases (there is reverse flow in the slot and a negative flow rate at an attack angle of 4 degrees), which weakens control over the boundary layer on the blade suction surface and increases flow loss in the cascade; (3) when the inlet location is biased towards the pressure surface (Slot 3), the sharp corners of the leading edge cause local flow separation near the slot inlet at an attack angle of 4 degrees, and as the attack angle decreases, the separation region expands and the flow rate in the slot decreases (there is reverse flow in the slot and a negative flow rate at an attack angle of −4 degrees), which weakens control over the boundary layer on the blade suction surface and increases flow loss in the cascade.

In general, when the slot inlet location was biased towards the suction surface, the flow rate in the slot increased at negative attack angles, the boundary layer on the suction surface was controlled more effectively, and the flow loss in the slotted cascade was smaller than that of the corresponding unslotted cascade at the negative attack angles. When the slot inlet location was biased towards the pressure surface, the flow rate in the slot increased at positive attack angles, the boundary layer on the suction surface was controlled more effectively, and the flow loss of the slotted cascade was smaller than that of the corresponding unslotted cascade at the positive attack angles. When the slot inlet location faced the leading edge, the flow rate in the slot and the flow loss of the slot had little change over a wide range of attack angles, and the cascade performed better than the corresponding unslotted cascade over the entire range of attack angles. Figure 9 Shows the influence of the inlet position of the slot on the flow rate in the slot and the control effect to the boundary layer on the suction surface.

3.2 Influence of the slot inlet width

The slot inlet width affects the flow field around the leading edge of the blade, the flow field inside the slot near the slot inlet, and the flow rate in the slot. To study the influence of the slot inlet width, the other slot parametres were held constant as the inlet width of Slot 1 was reduced from the original 1.0% of

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Table 4. *Cascade performance parametres*

i/(°)	Cascade	$\overline{\omega}$	$\Delta\beta/(°)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{slotr}/(\%)$	$m_{slotr}/(\%)$
0	Slot 1	0.0253	36.40	0.1070	3.41	0.81
0	Slot 2	0.0393	33.61	0.7161	6.37	0.35
0	Slot 3	0.0372	34.01	0.5974	7.17	0.45
−4	Slot 1	0.0331	31.74	0.3581	7.37	0.68
−4	Slot 2	0.0319	31.77	0.3517	7.52	0.68
−4	Slot 3	0.0534	30.36	1.0425	2.99	−0.15
4	Slot 1	0.0246	39.93	0.1063	3.50	0.81
4	Slot 2	0.0584	36.50	0.8474	4.15	−0.29
4	Slot 3	0.0260	38.99	0.2034	5.81	0.74

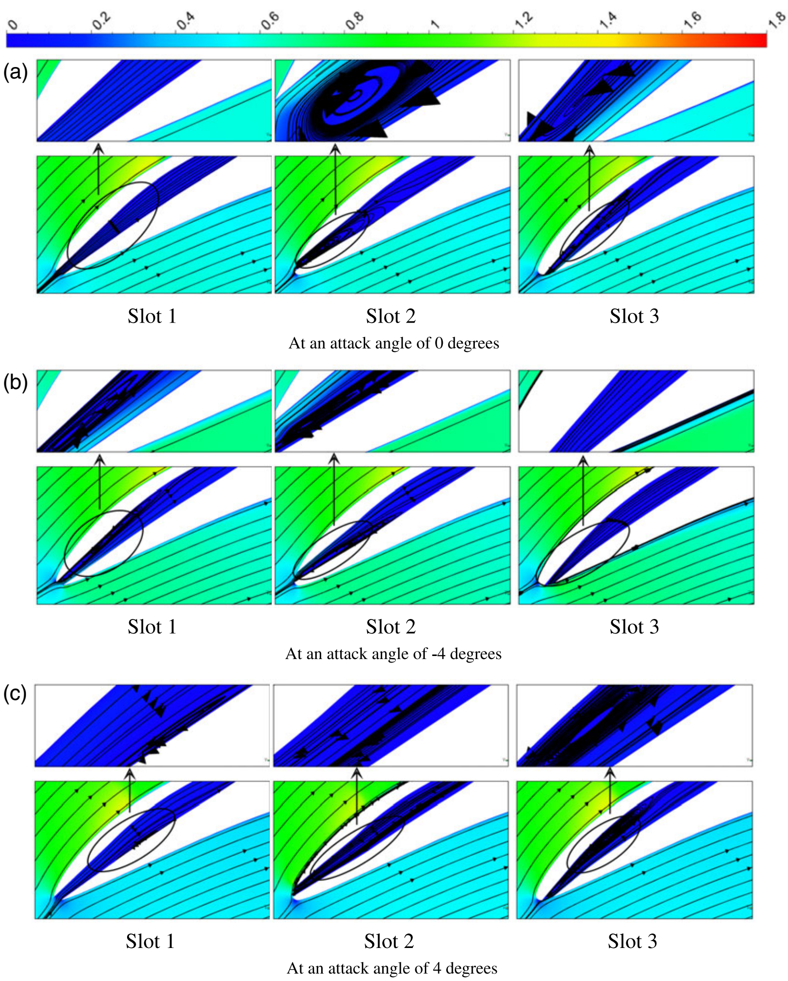

Figure 9. *Mach number contours near the leading edges.*

the blade axial chord length to 0.6%, forming Slot 4, and increased to 1.4%, forming Slot 5. The shapes of the slots are shown in Fig. 10.

Figure 11 shows influence of the inlet width on the flow field near the leading edge at attack angles of 0 degree and 6 degree. Compared with Slot 1, at attack angles of 0 degrees and 6 degrees, there were

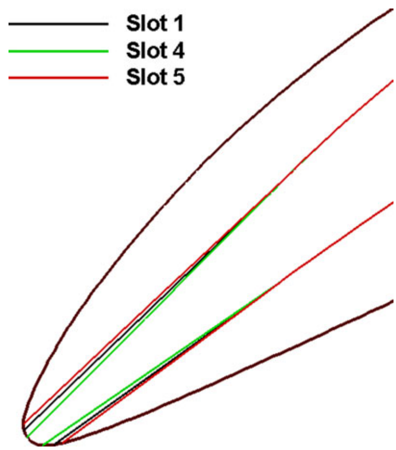

Figure 10. *Front part of the slotted blade.*

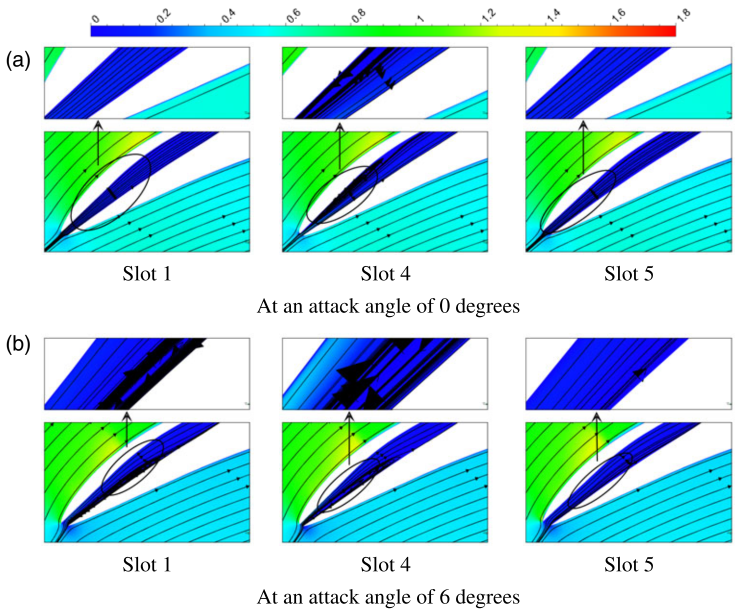

Figure 11. *Mach number contours near the leading edges.*

local flow separations in Slot 4 near the inlet due to the decrease in the inlet width and increase in slot expansion (see Fig. 11). This results in a decrease in the flow rate in the slot and increases in flow loss in the slot and flow loss in the cascade (see Table 5). Compared with Slot 1, Slot 5 has a wider inlet, but the flow rate in the slot remained unchanged at an attack angle of 0 degrees and increased slightly at an attack angle of 6 degrees (see Table 5). Since the slot outlet width was 0.5% of the blade axial chord length, which is the throat of the slot, increasing the inlet width does not affect the flow rate in the slot. However, because increasing the inlet width can reduce the sensitivity of the flow in the slot to the direction of the incoming flow, at a large positive attack angle, the flow rate in Slot 5 increased slightly, while the flow rates in Slot 1 and Slot 4 decreased. Figures 12 and 13 show influence of the inlet width

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Table 5. *Cascade performance parametres*

i/(°)	Cascade	d3/chord	$\overline{\omega}$	$\Delta\beta/(°)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{slotr}/(\%)$	$m_{slotr}/(\%)$
0	Slot 1	1%	0.0253	36.40	0.1070	3.41	0.81
0	Slot 4	0.6%	0.0266	35.93	0.2451	6.68	0.73
0	Slot 5	1.4%	0.0247	36.48	0.1000	3.28	0.81
6	Slot 1	1%	0.0268	41.22	0.1561	4.54	0.78
6	Slot 4	0.6%	0.0326	39.77	0.3694	6.69	0.59
6	Slot 5	1.4%	0.0324	40.80	0.0997	2.59	0.84

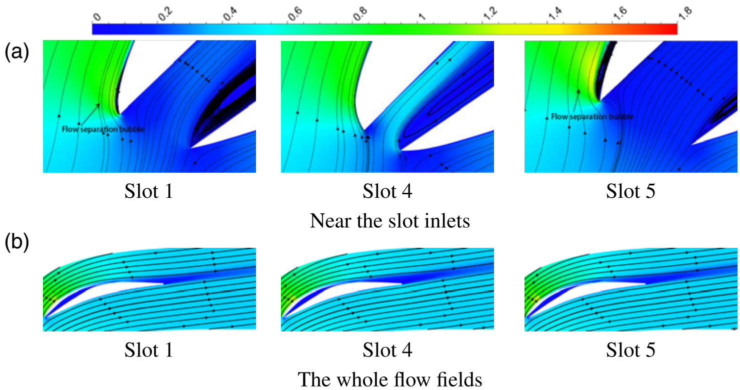

Figure 12. *Mach number contours at an attack angle of 6 degrees.*

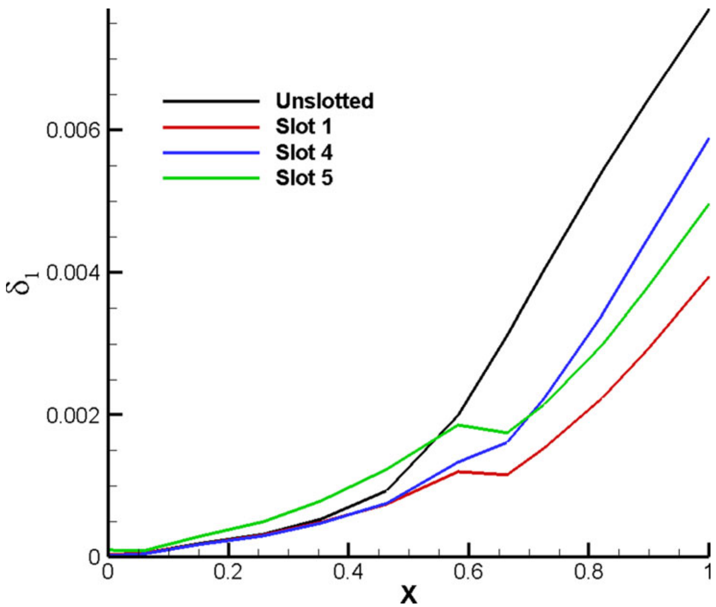

Figure 13. *Distribution of the thickness of the boundary layer on the suction surface at an attack angle of 6 degrees.*

on the boundary layer on the suction surface. Figure 12(a) shows that there is a flow separation bubble near the leading edge of the blade suction surface at a large attack angle. When the slot inlet width was reduced (Slot 4), the separation bubble disappeared due to the leading edge of the suction surface better

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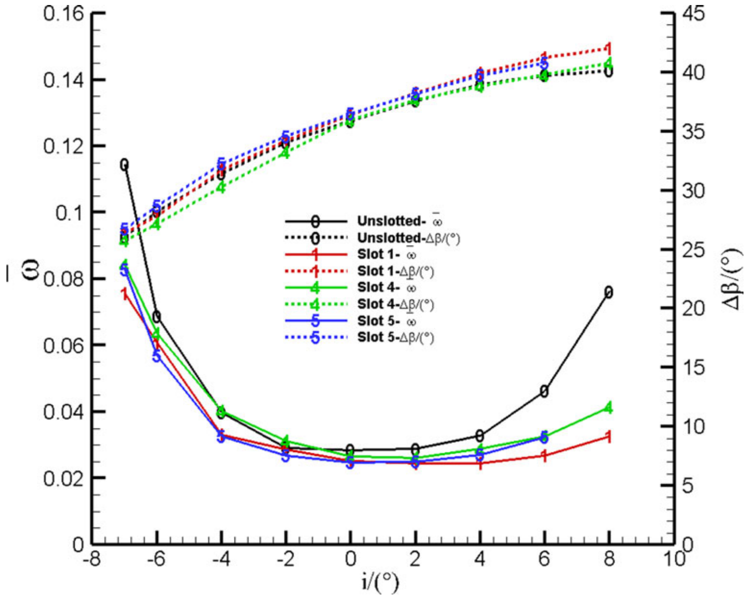

Figure 14. *Performance of slotted cascades with different slot inlet widths.*

guiding the incoming flow at a large attack angle. However, when the slot inlet width was increased (Slot 5), the separation bubble increased, increasing the thickness of the boundary layer on the suction surface (see Fig. 13). According to Fig. 12(b), when compared with Slot 1, the decrease in the flow rate in Slot 4 reduced the suppression of the development of the boundary layer on the suction surface, increasing the low-velocity area near the rear of the suction surface. Although increasing the flow rate in Slot 5 increased the suppression of the development of the boundary layer on the suction surface, because the boundary layer was relatively thick, the low-velocity region near the rear of the suction surface was still large. Therefore, the flow losses of the cascades of Slot 4 and Slot 5 increased.

According to the above analysis, the inlet width has a minor effect on the aerodynamic performance of the slotted cascade at a negative attack angle; however, at a large positive attack angle, decreasing the inlet width reduces the flow rate in the slot, reducing the effect of controlling the boundary layer on the suction surface. Increasing the inlet width may cause a separation bubble at the leading edge of the suction surface, increasing the flow loss in the suction surface. Figure 14 shows the performance of slotted cascades with different slot inlet widths. Figure 14 shows that in general, the slot inlet width has a small effect on the flow loss and flow turning angle of the cascade over the entire range of attack angles.

3.3 Influence of the slot shape

The wider the slot, the lower the flow speed in the slot and the smaller the wall friction loss of the flow in the slot. While keeping the other slot parametres constant, the shape of Slot 1 was expanded, forming Slot 6, and shrunk, forming Slot 7. The shapes of the slots are shown in Fig. 15.

Figure 16 shows that the shape of the slot has almost no effect on the flow loss and flow turning angle of the cascade over the entire range of the attack angle. Figure 17 shows flow characteristics in the slot. From the figure, as the slot width increased, the expansion of the front half of the slot increased, causing flow separation in the slot and increasing flow loss (seen in Fig. 18, where x is the distance from the slot inlet, with x=0 at the inlet, and x=1 at the outlet). However, according to Table 6, the flow loss in the slot accounts for a small proportion of the total loss of the cascade, and because the throat of the slot is

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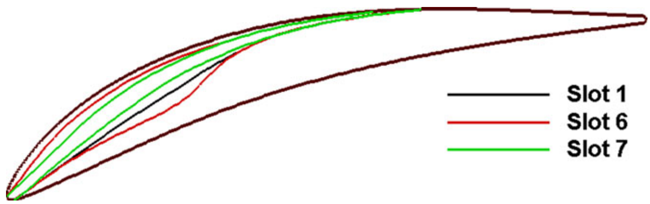

Figure 15. *Shapes of the slots.*

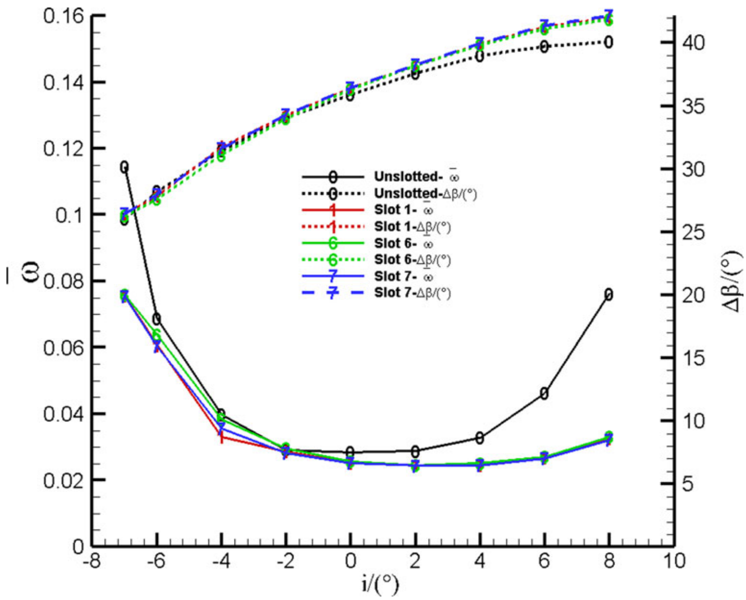

Figure 16. *Performance of cascades with different slot shapes.*

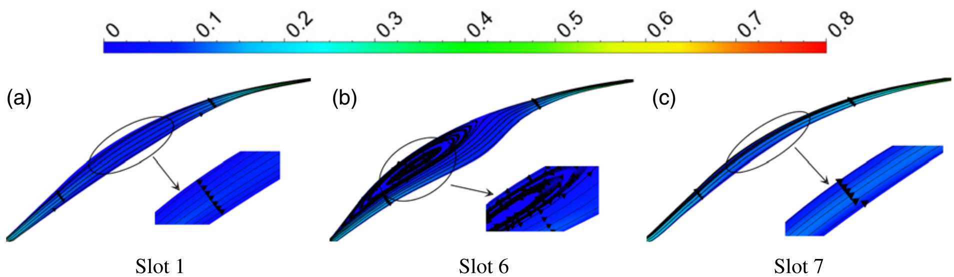

Figure 17. *Mach number contours and streamlines.*

not changed (at the outlet section), the flow rate in the slot is nearly unchanged. Therefore, the effect of changing the slot shape on the total loss of the cascade is negligible. Based on the above analysis, when the inlet and outlet of the slot are held constant, the shape of the slot mainly affects the flow in the slot, and its effect on the overall performance of the cascade is negligible due to the unchanged flow rate in the slot and the small flow loss in the slot relative to the total flow loss in the cascade.

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Table 6. *Performance parametres at an attack angle of 0 degrees*

Cascade	$\overline{\omega}$	$\Delta\beta/(^\circ)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{slotr}/(\%)$	$m_{sotr}/(\%)$
Slot 1	0.0253	36.40	0.1070	3.41	0.81
Slot 6	0.0257	36.31	0.1338	4.13	0.79
Slot 7	0.0252	36.43	0.1038	3.40	0.83

Table 7. *Performance parametres at an attack angle of 0 degrees*

Cascade	d_4/chord	$\overline{\omega}$	$\Delta\beta/(^\circ)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{slotr}/(\%)$	$m_{slotr}/(\%)$
Slot 7	0.5%	0.0252	36.43	0.1038	3.40	0.83
Slot 8	0.3%	0.0308	34.99	0.1582	1.42	0.48
Slot 9	0.8%	0.0239	36.75	0.1234	7.14	1.38

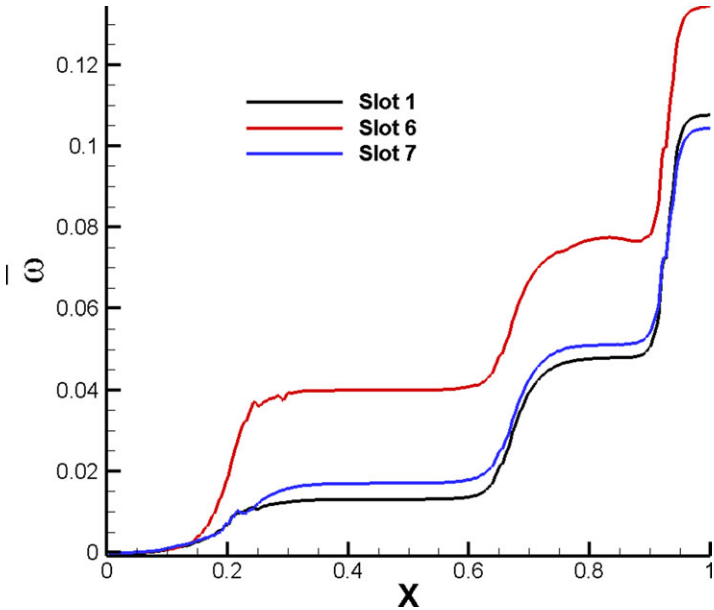

Figure 18. *Total pressure loss along the slot.*

3.4 Influence of the outlet width

Since the slot outlet of Slot 7 (shown in Fig. 15) is the throat of the slot, the width of the outlet determines the flow rate of the slot. While keeping the other parametres constant, the outlet width of Slot 7 was reduced from 0.5% of the axial chord length to 0.3%, forming Slot 8, and increased to 0.8%, forming Slot 9.

According to Table 7, the flow rate in the slot is essentially proportional to the outlet width. Therefore, the smaller the outlet width, the lower the flow rate in the slot and the smaller the ratio of flow loss in the slot to that in the cascade. As shown in Fig. 19, there were few differences in flow loss and flow turning angle between the cascades of Slot 7 and Slot 9 (corresponding to relative flow rates of 0.83 and 1.38 in the slots), but the flow loss in Slot 8 (corresponding to a relative flow rate of 0.48) was significantly larger than the flow loss in Slot 7 and Slot 9. Figure 19 shows that increasing the flow rate in the slot can improve control over the boundary layer on the suction surface. When the flow rate reached a certain value, the control effect was the best; increasing the flow rate further did not improve the effect.

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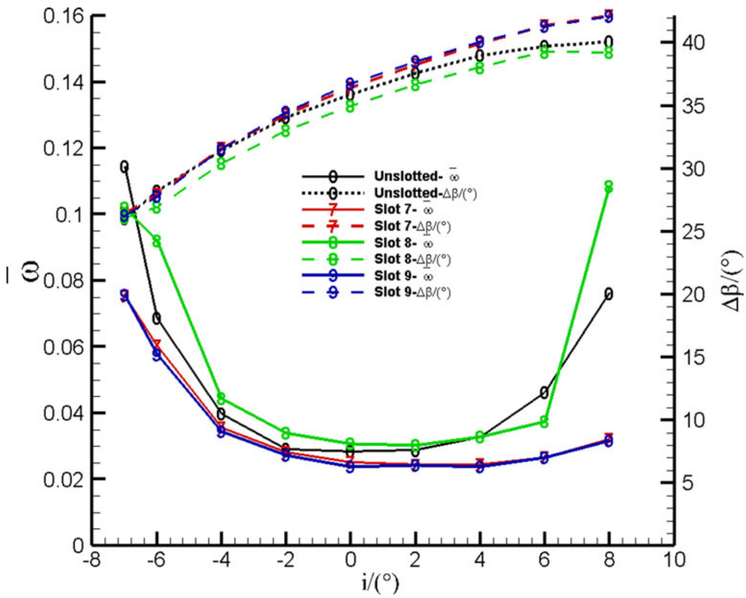

Figure 19. Performance parametres at an attack angle of 0 degrees.

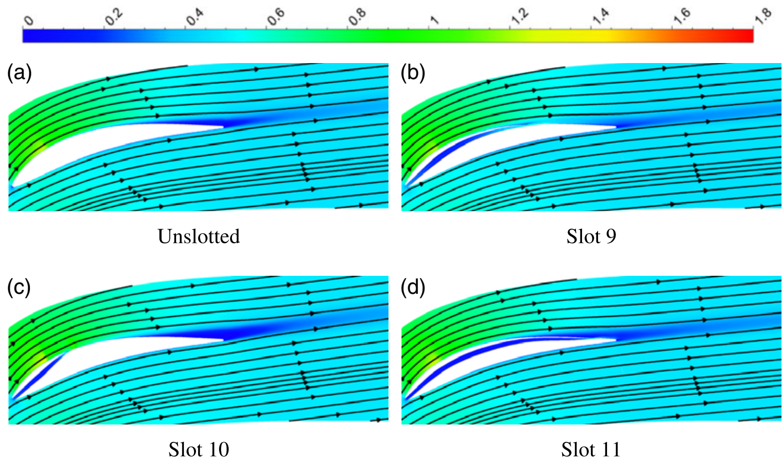

Figure 20. Mach number contours at an attack angle of 0 degrees.

3.5 Influence of the outlet width

The slot outlet location of Slot 9 is at 60% of the axial chord length, which is the starting position of a rapid increase in the thickness of the boundary layer on the suction surface (see Fig. 20(a)). To study the influence of the slot outlet location, the slot inlet and outlet widths were held constant as the slot outlet was moved to 25% of the axial chord length to form Slot 10 behind the local shock wave, and moved to 85% of the axial chord length to form Slot 11 (see Fig. 21).

If the outlet was on the suction surface at a location with a high isentropic Mach number (low pressure), the flow rate in the slot was high. Therefore, the flow rates in Slot 10, Slot 9 and Slot 11 decreased in turn and the flow losses in the slots increased in turn, mainly depending on the length of the slot (see Table 8). Figure 22 shows influence of the slot outlet on the cascade performance. From the figure, it can

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Table 8. *Performance parametres at an attack angle of 0 degrees*

Cascade	d_2/chord	$\overline{\omega}$	$\Delta\beta/(^\circ)$	$\overline{\omega}_{slot}$	$\overline{\omega}_{sl}/(\%)$	$m_{slotr}/(\%)$
Slot 9	60%	0.0239	36.75	0.1234	7.14	1.38
Slot 10	25%	0.0292	35.08	0.1048	5.96	1.66
Slot 11	85%	0.0280	36.53	0.1301	5.21	1.12

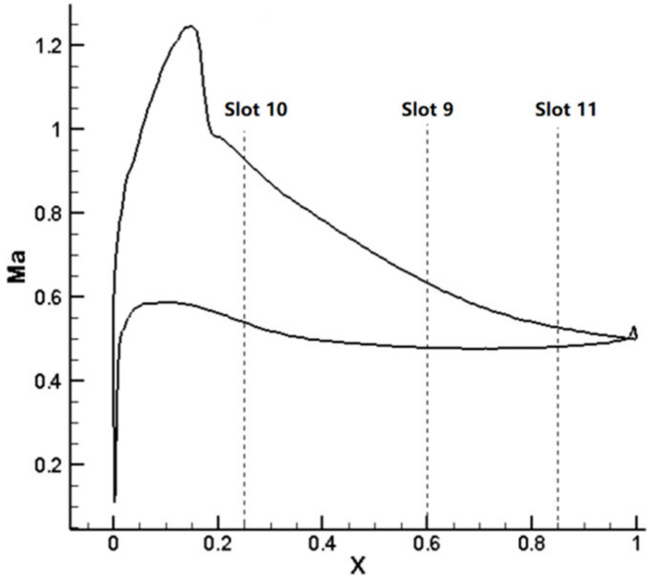

Figure 21. *Distribution isentropic Mach numbers on the surfaces of an unslotted blade and the outlet slot positions.*

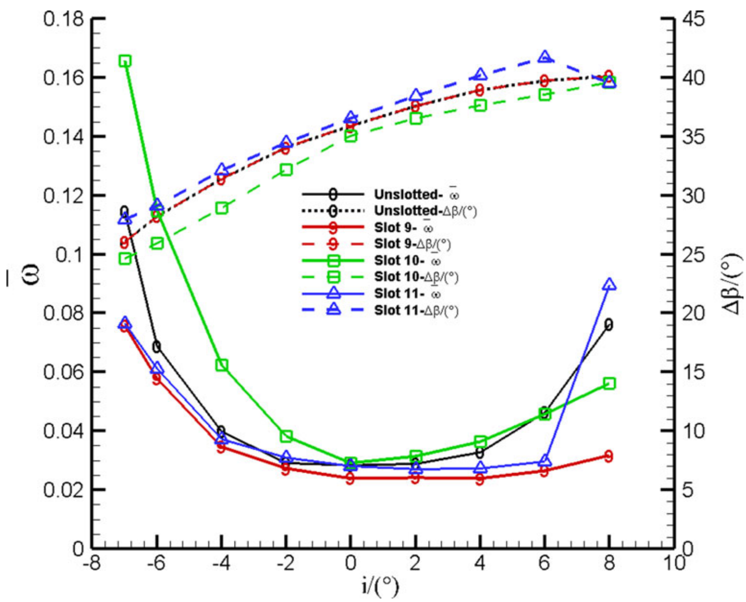

Figure 22. *Performance of cascades with different slot outlet locations.*

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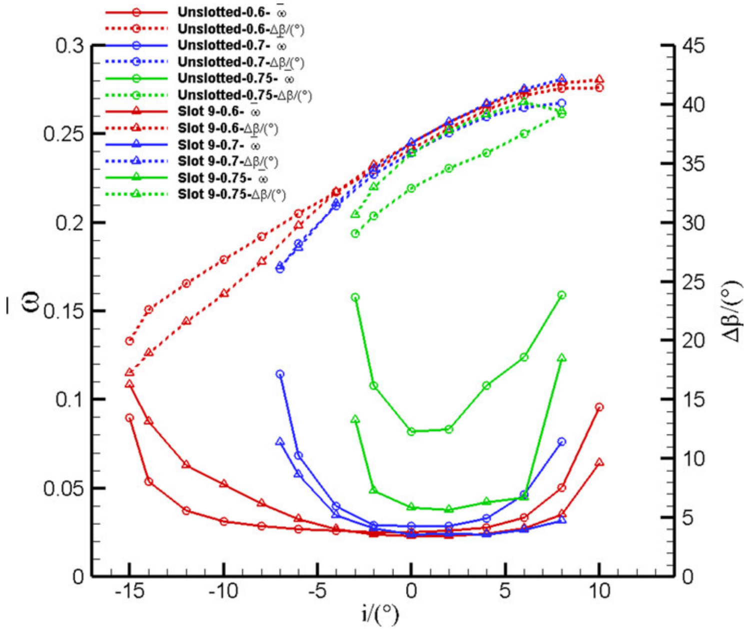

Figure 23. *Performance of slotted and unslotted cascades at various inlet Mach numbers.*

be seen that when the slot outlet was located at the starting position of a rapid increase in the thickness of the boundary layer on the suction surface (Slot 9), the boundary layer was controlled effectively by the slot jet at all attack angles, and the performance of the cascade was good. When the slot outlet was located near the trailing edge (Slot 11), the boundary layer was fully developed and difficult to control. Therefore, the performance of the cascade of Slot 11 is worse than that of Slot 9. When the slot outlet was located just behind the shock wave on the suction surface (Slot 10), where the boundary layer is thin, the jet had no effective control over the subsequent development of the boundary layer. Instead, due to flow loss in the slot and the mixing loss of the slot jet with the main flow, the flow loss at negative attack angles was greater than that of the unslotted cascade.

To further evaluate the aerodynamic performance of the slotted cascade at various inlet Mach numbers, the flow fields in the unslotted cascade and the slotted cascade of Slot 9 were simulated at different inlet Mach numbers. The performance of the unslotted and slotted cascades at inlet Mach numbers of 0.6, 0.7 and 0.75 are shown in Fig. 23. Moreover, the slot parametres of Slot 9 were applied to the highly loaded cascade with a diffusion factor of 0.6 (the key parametres are shown in Table 9), and the slotted blade is shown in Fig. 24. Figure 25 shows the performance of the unslotted and slotted cascades at inlet Mach numbers of 0.6, 0.7 and 0.8. From Figs 23 and 25, it can be seen that: (1) because the boundary layer on the suction surface at a positive attack angle is thicker than that at a negative attack angle, the performance is improved more by using slotting at a positive attack angle than at a negative attack angle; (2) the higher the inlet velocity of the cascade, the higher the flow momentum in the slot and the better the improvement; (3) the larger the diffusion factor, the thicker the boundary layer on the suction surface and the better the improvement; (4) because there is a small inverse pressure gradient in the suction surface at a negative attack angle, the performance improvement with slotting is weaker, with worse performance (increased flow loss) at negative attack angles.

According to the above study, the cascade of Slot 9 blades has the best performance, the key parametres of Slot 9 are shown in Table 10.

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Table 9. *Main parametres of the cascade*

Inlet Ma	τ	$\beta/(°)$	$\beta_2/(°)$	D
0.7 Ma	1.5	49	49	0.6

Table 10. *Key parametres of Slot 1*

d1/chord	d2/chord	d3/chord	d4/chord
0	60%	1%	0.8%

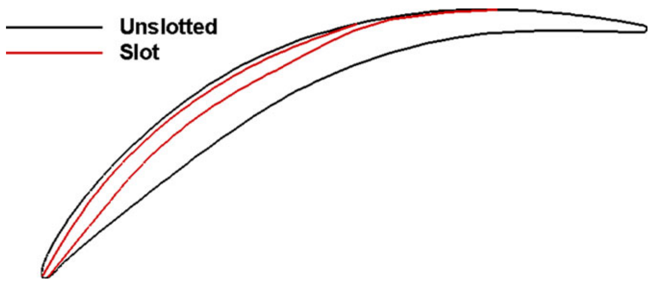

Figure 24. *The more highly loaded cascade.*

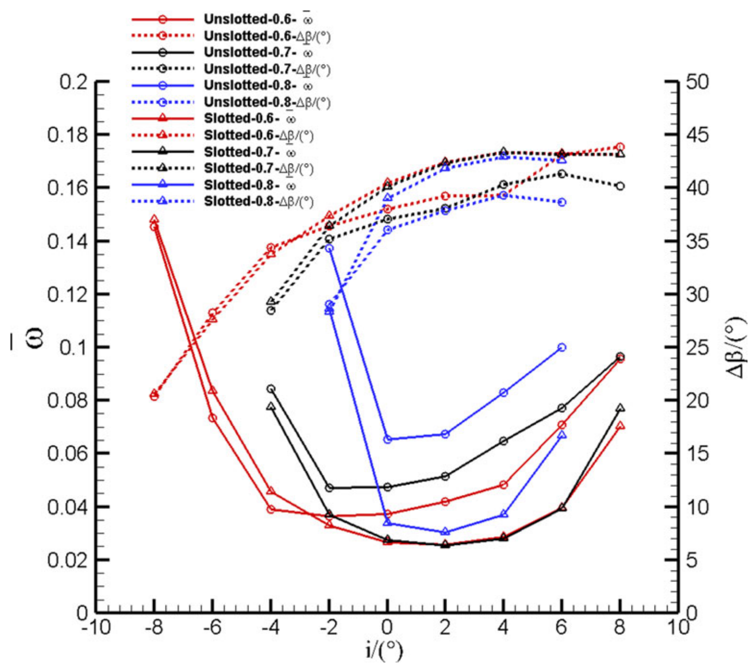

Figure 25. *Performance of the highly loaded cascade.*

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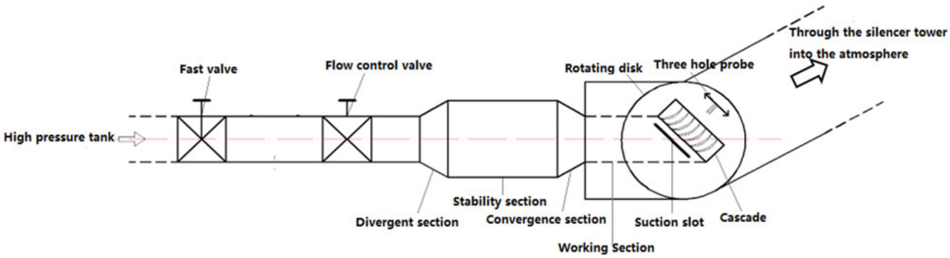

Figure 26. *Structure of the experiment bench.*

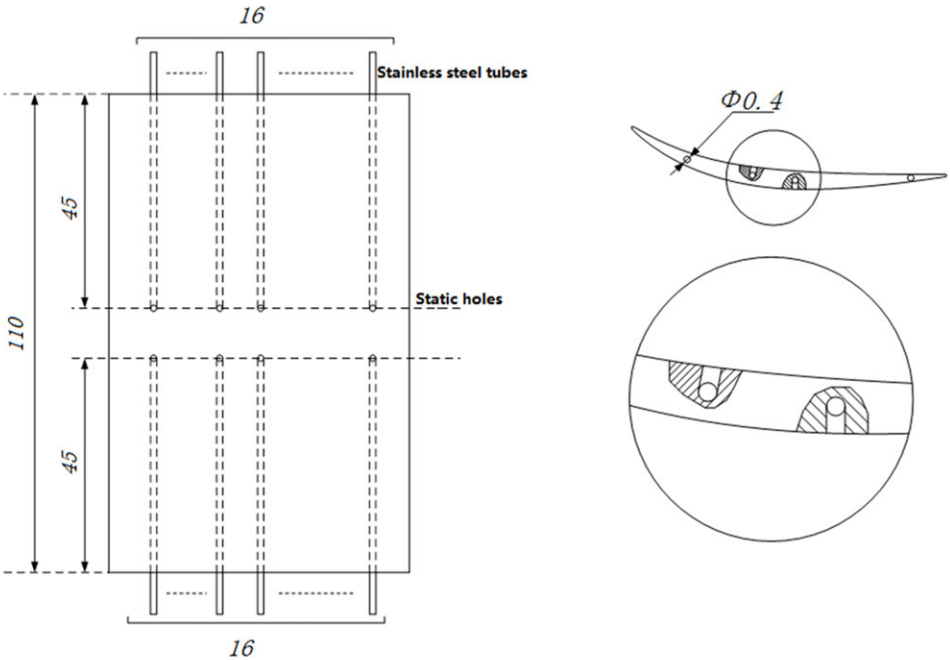

Figure 27. *Schematic diagram of static pressure holes drilled on the blade.*

4.0 Experiment investigation

4.1 Experiment method

The experiment was completed on the plane cascade experiment bench of the Nanjing University of Aeronautics and Astronautics. Figure 26 shows the structure of the experiment bench. The experimental bench was an intermittent wind tunnel, and the air source was a 100 m^3 high-pressure gas tank supplied by two 260 kW high-pressure compressors. The boundary layers at the upper and lower walls and side-walls were sucked by a 200 m^3 vacuum tank connected to three 200 kW vacuum pumps. The cascade height was 110 mm, and the length was 800 mm. The static pressure of the blade surface was measured by static holes, and the wake of the cascade was measured by three hole probes. Figure 27 shows a schematic diagram of the static holes drilled on the blade, and Fig. 28 shows a three-dimensional view of the cascade. In this experiment, the suction of boundary layers on the endwalls was not performed.

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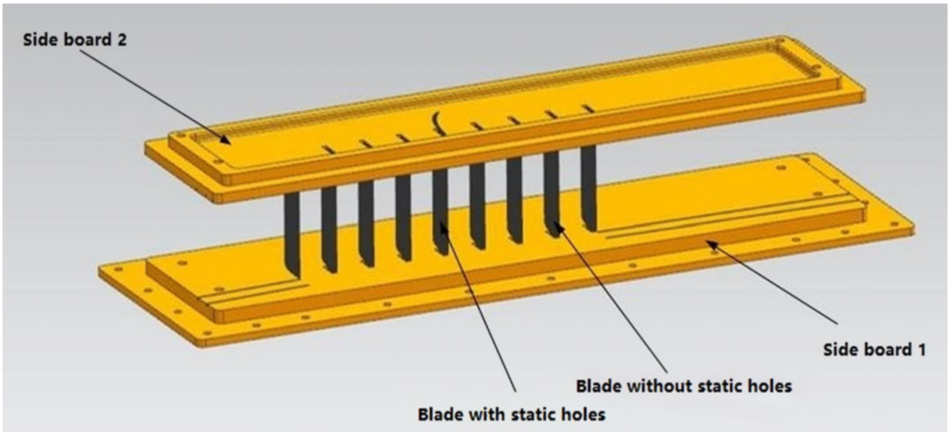

Figure 28. *Three-dimensional view of the cascade.*

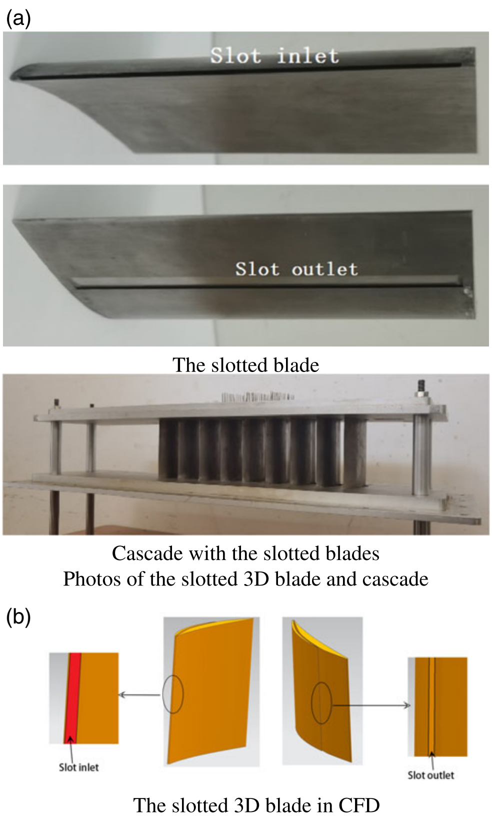

Figure 29. *The 3D slotted blade.*

4.2 Experimental results

An unslotted and a slotted 3D cascade were constructed. The unslotted 3D blade was formed by extending the unslotted 2D blade in the direction of blade height. The slotted 3D blade was formed by extending the 2D blade of Slot 9 in the direction of blade height. As shown in Fig. 29(a), the blade height is 120mm,

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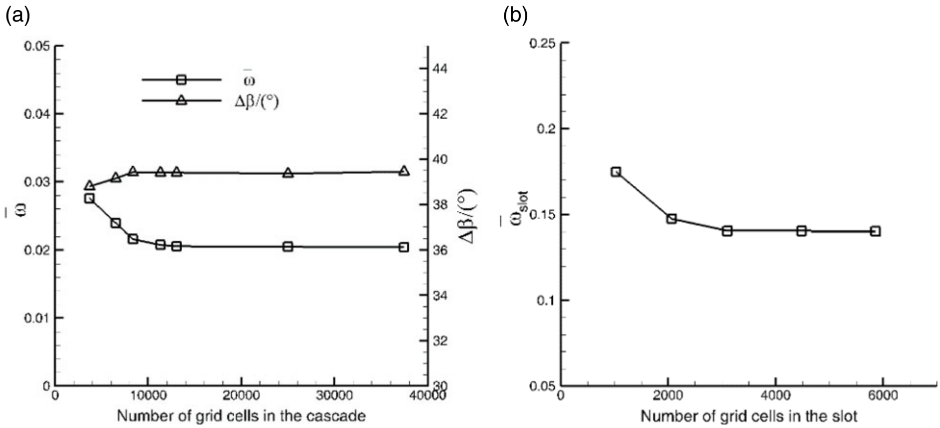

Total pressure loss in the slotted cascade

Total pressure loss in the slot

Figure 30. *Total pressure loss varies with the number of grid cells.*

length of the slot in the 3D blade was 110mm, which is equal to the distance between the two side walls of the working section (see Fig. 26). The slotted 3D blade is composed of two pieces, both ends of each piece are installed in the slots on the cascade side walls. The two 5mm margins at both ends of the blade are required for the installation. The slotted 3D blade in Computational Fluid Dynamics (CFD) is shown in Fig. 29(b). The coordinate error of the machined blades is less than 0.03mm; the machining accuracy of the blades was measured using a three coordinate measuring system.

The total pressure, static pressure at the inlet of the cascade and pressures in the three hole probe were collected for the measurement of aerodynamic parametres of the cascade flow field. Therefore, the measurement accuracy of flow field parametres depends on the pressure measurement accuracy. The accuracy of the pressure sensor is 0.25%, considering the signal noise in the transmission of the electrical signals and the sensor calibration error, the overall pressure measurement error is less than 1.0%. The coordinate error of the machined blades is less than 0.03 mm, namely the coordinate difference between the blade in the calculation model and in the experimental model is less than 0.03 mm, which can ensure good geometric consistency between the calculation model and the experimental model. Furthermore, the whole 3D flow fields of the working section were calculated to ensure the consistency of the simulated flow field with the experimental flow field.

The flow fields in the unslotted and slotted cascades were simulated, and the calculated and experimental performance of the cascades were compared to verify the calculation method used in previous research. To consider the influence of the boundary layers on the sidewalls of the test cascades, 3D flow fields in these test cascades were calculated, and the grid structure of the S1 surface (equal blade height surface) was the same as that in the previous 2D flow fields. Figure 30 shows the number of grid cells on the S1 surface, and the number of grid cells along the blade height was changed in proportion to the number on the S1 surface. As shown in Fig. 30, when the number of grid cells in the cascade was increased to 13,000 and the number of grid cells in the slot was increased to 2,400, the total pressure losses were nearly unchanged. Therefore, the corresponding two numbers 40,000 and 5,000 used in the previous and subsequent studies were enough.

Figure 31 shows the distribution of the isentropic Mach number on the blade surfaces of the slotted and unslotted cascades at an inlet Mach number of 0.75 and an attack angle of 0 degrees. Figure 32 shows the performance of the two cascades. As shown in Figs. 31 and 32, the calculated and experimental results were in good agreement; the flow loss in the slotted cascade was lower than that in the unslotted cascade, especially at a positive attack angle.

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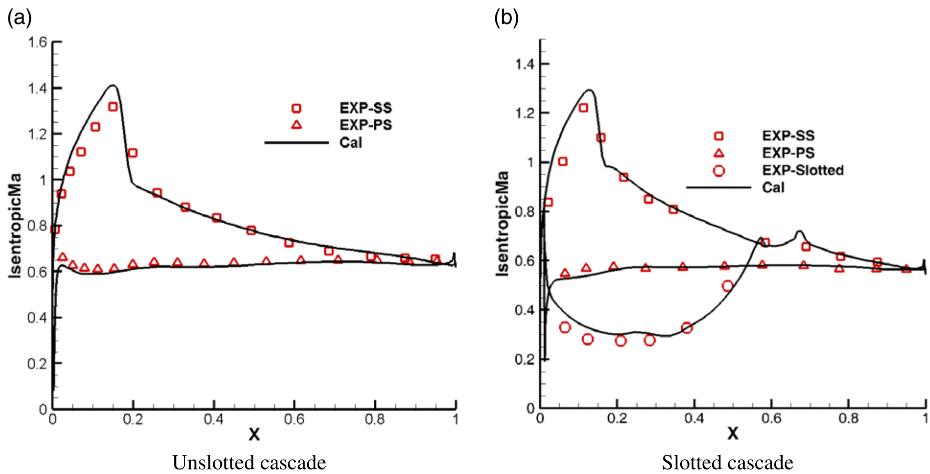

Figure 31. *Distribution of the isentropic Mach number on the blade surfaces.*

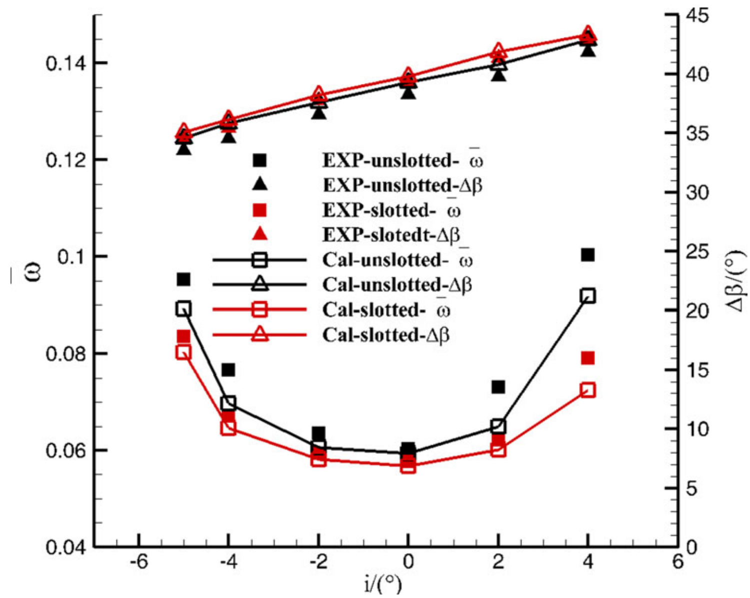

Figure 32. *Performance of the unslotted and slotted cascades.*

5.0 Conclusion

This paper proposes a novel method for creating the slot inside a compressor blade, with the inlet of the slot located at the leading edge of the blade and the outlet located at the suction surface, using the momentum of the incoming flow to form a high velocity jet that controls the boundary layer on the suction surface. Compared with the jet formed by the pressure difference between the pressure surface to the suction surface, the jet from the leading edge to the suction surface has greater momentum. The influence of the main parametres of the slot on the flow in the slot and in the cascade with a diffusion factor of 0.45 was investigated, and the aerodynamic performance of slotted and unslotted cascades with diffusion factors of 0.45 and 0.60 were compared. The flow fields of the unslotted and slotted cascades were measured. The following conclusions can be drawn.

(1) When the slot inlet location is unbiased at the leading edge, the flow rate and the flow loss in the slot change little over a wide range of angles of attack, and the cascade performs better than the corresponding unslotted cascade over the entire range of angles of attack. When the slot inlet location is biased, for example, towards the pressure surface, then at positive angles of attack, the flow rate in the slot becomes larger, the suction surface boundary layer is controlled more effectively, and flow loss of the slotted cascade becomes smaller than the corresponding unslotted cascade. Conversely, when the slot inlet is biased towards the suction surface, the same effects occur at negative angles of attack.

(2) The inlet width has a small effect on the aerodynamic performance of the cascade at a negative attack angle; however, at a large positive attack angle, decreasing the inlet width reduces the flow rate in the slot, reducing the effect of controlling the boundary layer on the suction surface. Increasing the inlet width may cause separation bubbles at the leading edge of the suction surface, increasing flow loss in the suction surface.

(3) When the inlet and outlet of the slot are kept constant, the shape of the slot mainly affects the flow in the slot, and its effect on the overall performance of the cascade is negligible due to the constant flow rate in the slot and the small flow loss in the slot relative to the total flow loss in the cascade.

(4) Increasing the flow rate in the slot can improve control over the boundary layer on the suction surface; when the flow rate reaches a certain value, the control effect is optimal, and increasing the flow rate further does not improve the effect.

(5) When the slot outlet is located at the starting position of the rapid increase in the thickness of the boundary layer on the suction surface, the boundary layer can be controlled effectively by the slot jet at all attack angles, and the performance of the cascade is good; when the slot outlet is located near the trailing edge, the boundary layer is already fully developed and thus difficult to control. When the slot outlet is located just behind the shock wave on the suction surface, where the boundary layer is thin, the jet has no effective control over the subsequent development of the boundary layer. At this location, due to flow loss in the slot and the mixing loss of the slot jet with the main flow, the flow loss at negative attack angles is greater than that of the unslotted cascade.

(6) Based on the comparison of the performance of the unslotted and slotted cascades, because the boundary layer on the suction surface is thicker at positive attack angles than at negative attack angles, the performance improves more with slotting at positive attack angles than at negative attack angles. The higher the inlet velocity of the cascade, the larger the flow momentum in the slot and the better the improvement; the larger the diffusion factor, the thicker the boundary layer on the suction surface and the better the improvement. Because there is a small adverse pressure gradient in the suction surface at negative attack angles, the performance improvement from slotting is weaker, and the performance can even worsen (increased flow loss) at negative attack angles.

(7) The experimental and calculated results are in good agreement, which verifies the accuracy of the calculation method in this paper as well as the feasibility of slotting for suppressing the boundary layer on the suction surface and reducing flow loss.

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