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Original Paper (Invited)

Numerical Study of Passive Control with Slotted Blading in Highly Loaded Compressor Cascade at Low Mach Number

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Abstract

With the aim to increase blade loadings and stable operating range in highly loaded compressors, this article has been conducted to explore, through a numerical parametric study, the potential of passive control using slotted bladings in cascade configurations. The objective of this numerical investigation is to analyze the influence of location, width and slope of the slots and therefore identify the optimal configuration. The approach is based on two dimensional cascade geometry, low speed regime, steady state and turbulent RANS model. The results show the efficiency of this passive technique to delay separation and enhance aerodynamic performances of the compressor cascade. A maximum of 28.3% reduction in loss coefficient have been reached, the flow turning is increased with approximately 5^0 and high loading over a wide range of angle of attack have been obtained for the optimized control parameter.

Keywords: 2D cascade, Highly loaded compressor, Separation, Passive control, Slotted blading, Low Mach number.

1. Introduction

It is well known that separation is the main factor to reduce drastically the aerodynamic performances of compressors in turbo-engines. It decreases the operating range by generating instability such as rotating stall and surge, and reduces efficiency by producing high losses. The evident objective of engineers facing this undesirable phenomenon is to control it by mitigating or eliminating the separation zones. A lot of researches have been done in the area of flow control but the passive control method remains the preferable tools because of their simplicity and cost effectiveness. The basic principle of passive flow control is to energize the low momentum layers near solid surface without adding extra energy in order to overcome stronger adverse pressure gradient and therefore avoid the flow separation. All of the passive approaches used in turbo machinery such as vortex generators, Gurney flaps, slots and tandem bladings have been derived from methods successfully applied to aircraft wings. The slots represent one of the older methods to control boundary layer. To the author's knowledge, there have been a few previous investigations of slots in real turbo machinery applications. One of the extensive investigations which was conducted to determine the potential of slotted cascades for obtaining a wide range of operation and a large stall margin of compressor stages are summarized by Wennerstrom [8]. The investigation includes testing of three slotted rotor and three slotted stator. Rotor slots were located at 50 percent chord and stator slots at 55 percent chord. The results indicated good performance for the blade row at midspan regions but poor performance near the walls. The relative effectiveness of the slots at midspan and their ineffectiveness near both end walls was attributed to chordal location of the slots and their inability to reduce the large secondary flows in the wall regions. The addition of blade end slots upstream of the original slots and the secondary flow fences was found to be ineffective and the loss coefficients were not reduced by these modifications. It was concluded that slots might be expected to have some positive effect at low aspect ratio and lower Mach numbers; otherwise their effect might be negative. Furthermore, two recent numerical studies were carried out by Zhou et al [9],[10] using slot treatment technology from pressure surface to suction surface of blade to control boundary layer. In this reference [9], three kinds of blade slot treatments were designed and the results indicate that the performance of cascade can be improved by effective slot position and structure. In another work [10] the slot solution was designed on the stator blade in order to explore their effect on the single stage compressor characteristic. The slot effect was positive to improve compressor performance and enlarge stable operation region. The present article focuses on numerical investigation which explores the optimal potential of the passive control method through a parametric study. The passive control is based on air injection achieved by linking the low pressure region at suction side with high pressure

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region at pressure side using slotted blading. The mass flow rate of slot jet mainly depends on the pressure difference between the two sides of the blade. Our objective is to find the best configuration of cascade where the slot jet energize the low momentum flow in order to delay or eliminate the separation boundary layer and reduce the losses to enhance the aerodynamic performances of the highly loaded compressor cascades. Different slot locations, slot slope angles and slot widths are studied in order to achieve this objective.

2. Numerical Procedure

In the preprocessing step, the geometry and mesh are developed in GAMBIT. The geometry definition gives the study field limited, in streamwise, by inlet and outlet located at approximately 1.2 chords away from the leading edge and trailing edge, respectively, and, in pitchwise, by two periodic identified by solidity σ=1.25. Between these four boundaries, the high cambered blade NACA 65(18)10 profile has been chosen. It is built by creating real edges from a 26 points table, taken from the reference of Emery et al [7]. The blade is provided by a slot with constant section Y and characterized by a stagger angle λ =13^0 and a chord length c =0.127m, fig. 1.

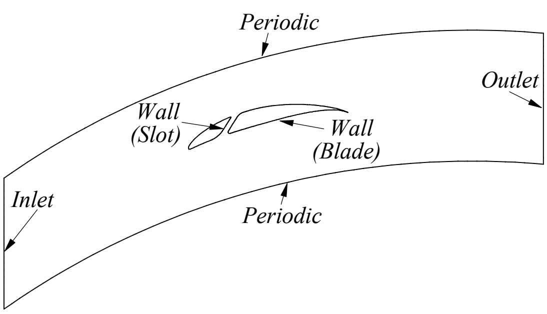


Fig. 1 Geometric model with slotted blading

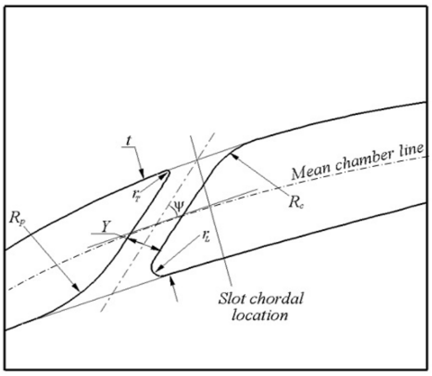


Fig. 2 Slot geometry nomenclature

It is well known that the existence of singular points, which represent in this investigation the slot corners, provoke a pressure gradients between their upstream and downstream and consequently the separation of boundary layer in these zones. The remedy of this problem is to design slot geometry with curves instead broken lines as shown in fig. 2. The slot data are chosen from the reference reported by Linder et al [4]. They are summarized as follow:

Y: Width slot

t : Thickness at intersection of slot axis and mean camber line

r_T: Slot trailing edge radius ; 0.000127m

r_L: Slot leading edge radius ; 0.097t

R_c: Coanda radius ; 0.792t

R_p: Pressure surface radius; 1.73t

ψ : Angle formed by slot axis and mean camber line.

The grid generation represents the subdivision of the study field into discrete control volumes. Two types of mesh are applied, a structured mesh in the vicinity of blade surfaces to capture the severe gradients in the region of boundary layer and an unstructured mesh in the remainder of computational domain. The wall functions model needs to adjust the thickness of neighboring cells to blade surface with the value of 0.005 chords in order to satisfy the condition $30<y^+<100$, where, y^+ is the characteristic non dimensional distance from the wall. The total number of cells for a typical cascade configuration is about 26000. The independence grid-solution is obtained after several attempting improvements. Since each model needs a different mesh, it is inappropriate to show all slotted cascades tested in this work. Therefore, only representative mesh of slotted cascades with a chordal location X=0.35c, a width Y=4mm, and a slope ψ=45^0 is shown in fig.3.

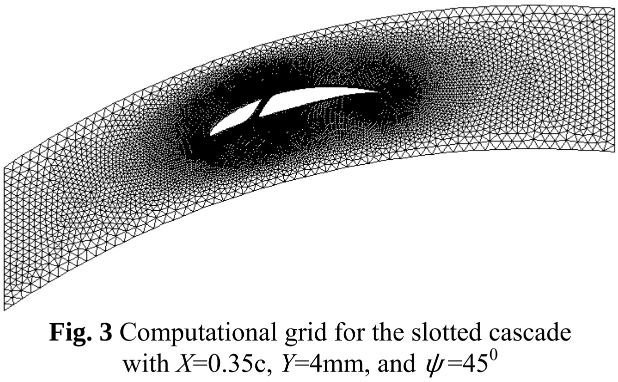


Fig. 3 Computational grid for the slotted cascade
with X=0.35c, Y=4mm, and ψ=45^0

In the processing step, The FLUENT solver is used as a CFD-tool for solving the governing equations. The flow model considered in the present investigation is based on two dimensional situation, steady state, incompressible regime and k-ε turbulent model with wall functions. Therefore, the governing equations representing continuity, momentum, k- and ε- transport equation are discretized using the finite volume approach applied in FLUENT solver. It is convenient to simulate one flow passage limited by two interfaces because the row compressor represents a cascade with an infinite number of blades. At these interfaces or periodic boundaries the principle of ghost cells is introduced. Consequently, the real and ghost cells are allowed to overlap without need to interpolate the flow variables with another blade passages. At all solid walls such as pressure, suction surfaces, and slot walls; the no slip and impermeability condition is imposed. At the inlet, the velocity components, turbulence intensity and hydraulic diameter are specified. On the contrary, at the outlet, the velocity components and turbulence parameters are extrapolated from neighboring interior cells.

3. Investigation with Reference Blading and Code Validation Results

To validate the numerical model; a comparison between computational and experimental results is carried out. The experimental data comes from the Emery's report [7]. The comparison is shown in fig. 4 for the surface pressure distribution on a NACA 65(18)10 cascade without slots and reported in terms of relative dynamic pressure, $S=2(P_{01}-P)/(\rho W_1^2)$, where, P_{01} is the upstream stagnation pressure. The operating conditions are set at free-stream Mach number M=0.085 and Reynolds number, based on blade chord, Re=245000. The cascade has a stagger angle λ =13^0, blade angle of attack α_l=17^0 and solidity σ =1.25. The shown result in Figure 4 and other numerical outputs for many tested configurations give a good agreement with experimental data cited in [7].

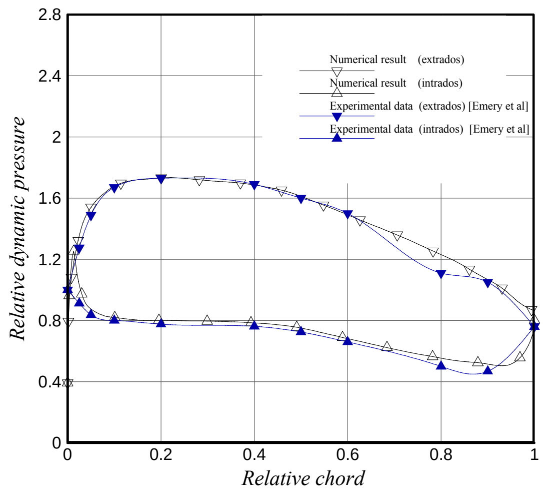


Fig. 4 Comparison between experimental and numerical results for blade surface pressure distributions without slot (α_l=17^0, λ=13^0 and σ=1.25)

As the objective from this study is to prevent boundary layer separation and to broaden the stable operating range of the cascade via slotted blading, the convenient operating range is defined as the range where the total losses are lower than twice the minimum value. The computational results indicates that the minimum losses occur close to the design point at β_1=19^0, fig.15.

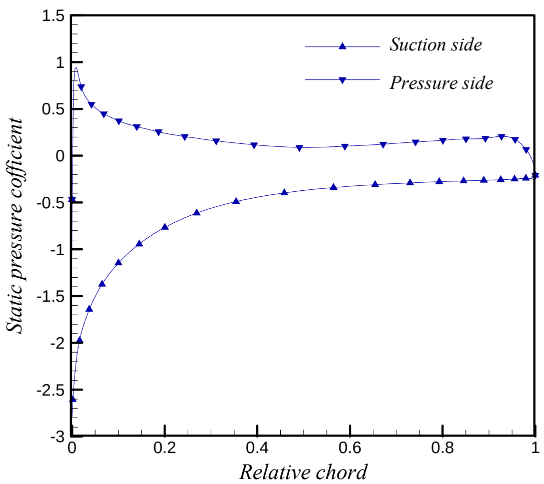


Fig. 5 Static pressure coefficient on blade surfaces without slot (α_1=39^0, λ=13^0 and σ=1.25)

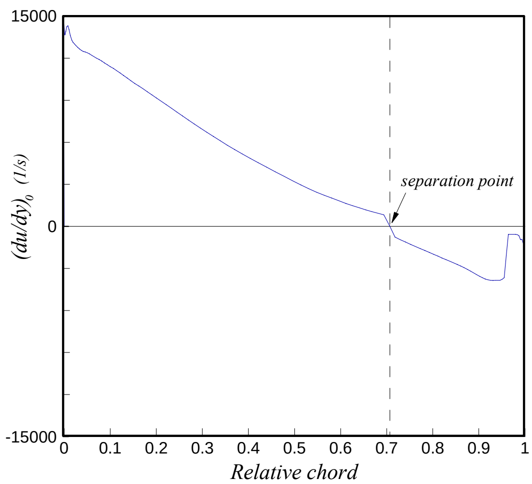


Fig. 6 First circumferential derivative of axial axial velocity at suction surface without slot (α_1=39^0, λ=13^0 and σ=1.25)

Thus, the maximum negative incidence is set to 4^0 and the maximum positive incidence to 32^0. Concerning the onset of flow separation, it must to be taken into consideration that the standard k/ε-turbulence model generally tends to delay the prediction of boundary layer separation. Consequently, the parametric study will be carried out, in the next part, on the basis of a cascade configuration with a constant angle of attack α_1=39^0 which gives a beginning of separation at about 70% of the relative chord length. The figures 5 and 6 show this separation zone. In the former the pressure gradient starts leveling off and in the latter the first circumferential derivative of axial velocity at suction surface is vanished.

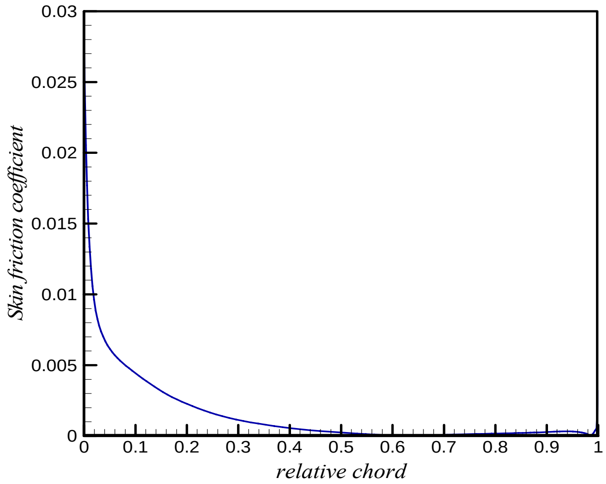


Fig. 7 Skin friction coefficient on suction surface without slot (α_1=39^0, λ=13^0 and σ=1.25)

4. Parametric Study

The influences of location, width and slope of the slot are successively examined. Each control parameter is studied independently and the efficiency of control is analyzed on the basis of the mass averaged total loss coefficient and the turning angle.

4.1 Effect of Slot Location

The objective of this section is to identify the optimal slot location by fixing the width and slope as Y=2mm and ψ =45^0. The analyze is carried out on eight locations, seven adjacent positions are separated with 10% of the relative chord length and one other position is located at 35% of the relative chord length. The procedure to determine the location of the slot is to draw the slot centerline at an angle ψ with the meanline and passed it through the suction surface. The produced intersection represents the desired chordal slot location X on the suction side. Figure 8 shows that the lower loss coefficients, which oscillate around the value 0.145, are located in the range of locations between 30% and 50% of the relative chord length and the best loss coefficient is identified when the slot is positioned at 35% of the relative chord length.

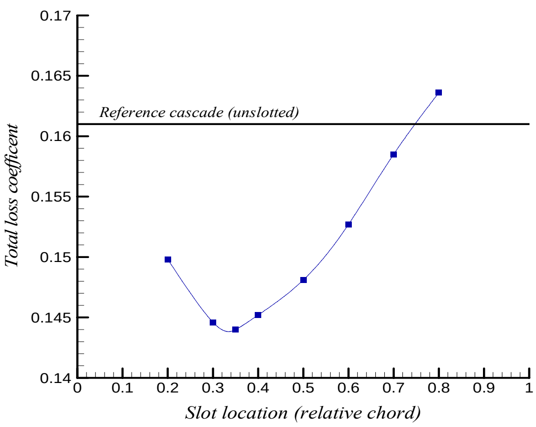


Fig. 8 Loss coefficient for different slot locations (Y=2mm and ψ=45^0)

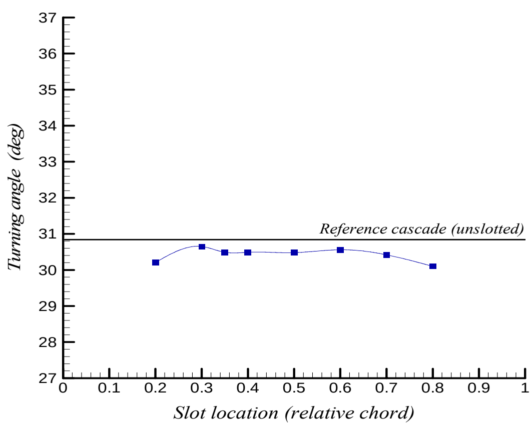


Fig. 9 Turning angle for different slot locations (Y=2mm and ψ=45^0)

First, since the position of separation point is located at about 70% of the relative chord length, fig. 6, and the minimum pressure point is close to the leading edge, fig. 5, the optimal location X=0.35c confirms the Linder's criterion [4], which said that the slot would be located approximately halfway between the minimum pressure point and the separation point. This criterion, deduced from experimental data, can be validate using predicted skin friction value close to zero at 40% chord and boundary layer form factor evolution shown in figure 7. If it is assume that NACA profile have, due to their form, same kind of suction side evolution of skin friction or diffusion factor, this criterion may be applied over a wide range of inlet conditions.

Second, the reason for the higher losses marked in the region downstream the location X=0.5c, in particular in the separation zone, is the insufficient slot jet momentum to energize the surface suction boundary layer. This insufficient slot jet momentum is resulted from the weak difference pressure level between suction and pressure surface shown by the static pressure coefficient distribution in fig. 5. Concerning the slot located in the detachment zone, it is inadvisable to exhaust the slot flow into the separated region because it cannot effectively turn the primary flow back toward the suction surface.

Third, in spite the high difference pressure level in the region upstream the location *X*=0.3*c*, illustrated by the static pressure coefficient distribution, fig. 5, the loss coefficient appear high. This increase is produced by the mixing losses due to the high velocity of the main flow in this region. The figure 9 shows that the different locations of the slot used with the width *Y*=2mm and the slope $\psi=45^0$ influences negatively but slightly the turning angle.

4.2 Effect of Slot Width

The influence of slot width is studied for the optimal position *X*=0.35*c* and the fixed value of slot slope $\psi=45^0$. The results are reported in figure 10 and 11 for the different widths from 1 to 11mm. The positive effect is obtained when the width is increased as far as the value *Y*=6mm. The two widths *Y*=6mm and *Y*=7mm give the same lower value of loss coefficient but the slot width *Y*=7mm leads to high turning angle, fig. 11. Therefore, the optimum corresponds to the threshold value *Y*=7mm. Beyond this optimal value, the increasing in the level of losses represents the sign of the thicker of boundary layer set by the higher values of slot width.

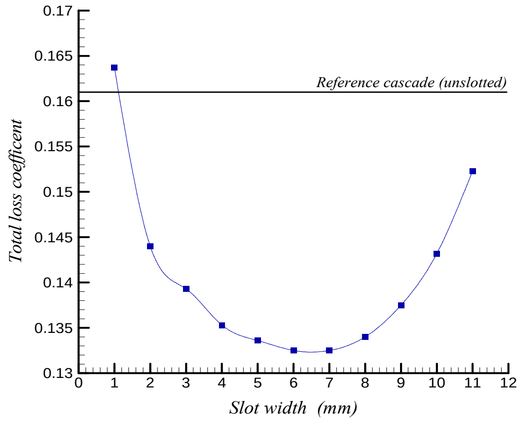


Fig. 10 Loss coefficient for different slot widths (*X*=0.35*c* and $\psi=45^0$)

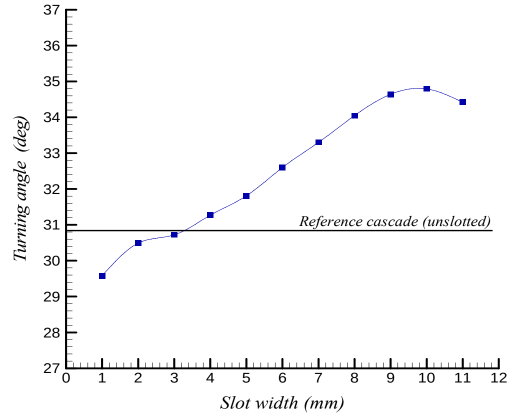


Fig. 11 Turning angle for different slot widths (*X*=0.35*c* and $\psi=45^0$)

4.3 Effect of Slot Slope

Similarly, in order to analyze the influence of slot slope, the optimal control parameters such the position *X*=0.35*c* and the width *Y*=7mm are used for three values of the angle ψ ; 30^0, 45^0 and 60^0. The results, shown in fig. 12, indicate that the best result corresponds to the lowest tested angle $\psi=30^0$. In fact, with the fixed exit slot on the position *X*=0.35*c*, at suction side, and the different entries slot, at pressure side, which correspond to the angles $\psi=30^0$, 45^0 and 60^0, the pressure difference, between the entry and the exit of slot, increases when the slot slope becomes less stiff. This is confirmed by the static pressure coefficient distribution in fig. 5.

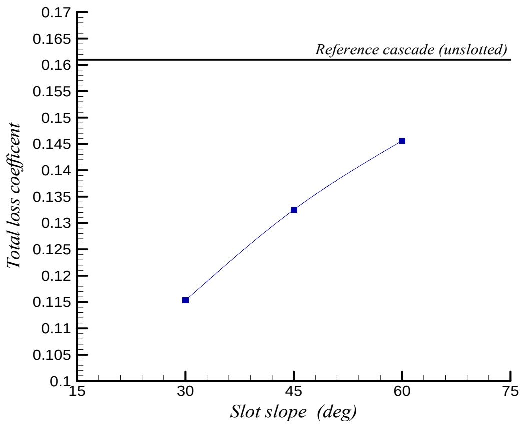


Fig. 12 Loss coefficient for different slot slopes (*X*=0.35*c* and *Y*=7mm)

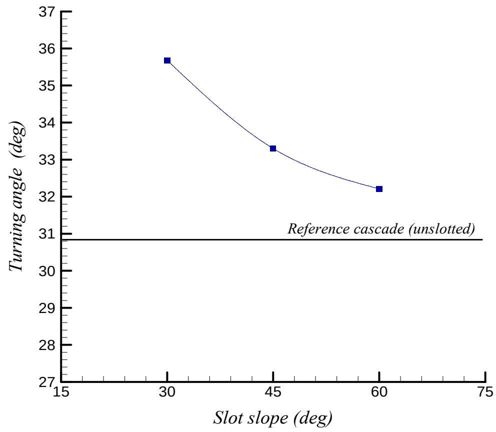
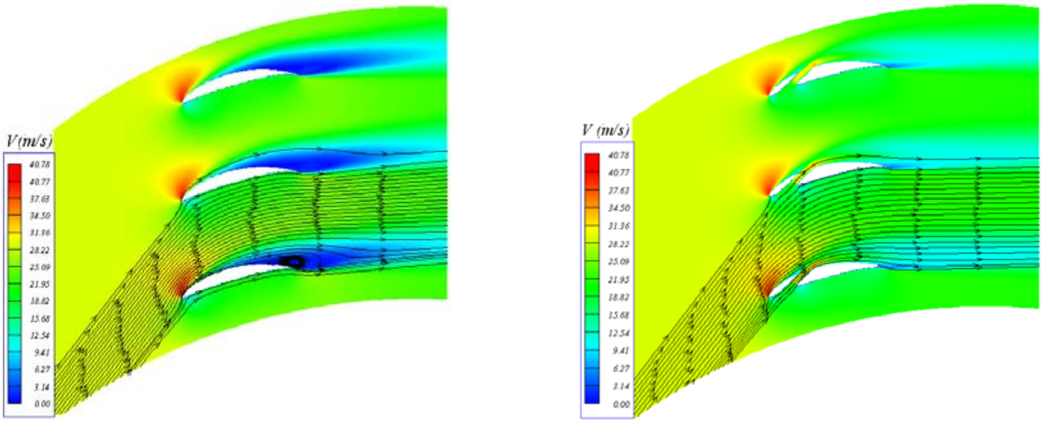


Fig. 13 Turning angle for different slot slopes (*X*=0.35*c* and *Y*=7mm)

The numerical experimentation presented here provides us different solutions to reduce the mass averaged loss coefficient and increase the turning angle. The best solution is obtained for a slot located at 35% of relative chord length, a slot width *Y*=7mm and a slope, defined by the angle between the slot centerline and the mean chamber line, $\psi=30^0$. The relative reduction of loss coefficient is up to 28.3% and the turning angle increase with 5^0, fig. 13.



(a) Unslotted cascade **(b)** Slotted cascade

Fig. 14 Velocity contours and streamlines for the best configuration (X=0.35c, Y=7mm and ψ=30^0)

The figures 14 shows the comparison of velocity magnitude fields and streamlines between the slotted and unslotted cascades and illustrates the significant influence of the optimal slot jet momentum to eliminate boundary layer separation. The variations of loss coefficients with angles of attack for the both simulated cascades, slotted and unslotted, are illustrated in fig. 15. The lower values of loss coefficient are observed approximately over the range where the separation is manifested. In these regions, the passive control with slotted blading proves his efficiency to eliminate the flow detachment. Over the remainder range of angles of attack, the use of slot leads to high profile loss coefficients. This may be due to expected process of flow energization leading to higher skin friction and higher mixing loss. The expected rise in the loss coefficient outside the separation range remains within tolerable limits.

In order to complete the analysis, figure 16 shows the turning angle evolution with various angles of attack both for unslotted and slotted configuration. Comparison between experimental data and numerical results with unslotted configuration shows a quantitative difference, but there is a good qualitative tendency between them. The positive effect of slotted configuration appears in the separation region which the stall point is shifted to right side in order to broaden the range of operation. Concerning the turning angle distribution, the difference between the experimental data and numerical one shows a systematic gap of about 5^0. We have not checked the reason of this difference in turning angle. The only comment we can give at that time is that our calculations are in 2D one and the experiments are done in a real cascade with a specific aspect ratio which is not the case for 2D calculations.

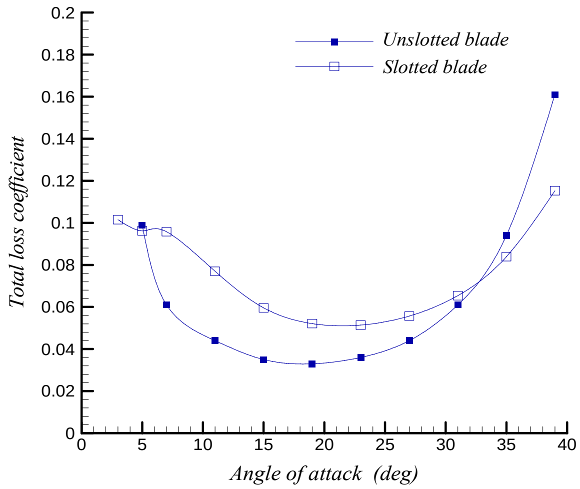


Fig. 15 Variation of loss coefficient with angles of attack of slotted and unslotted blading

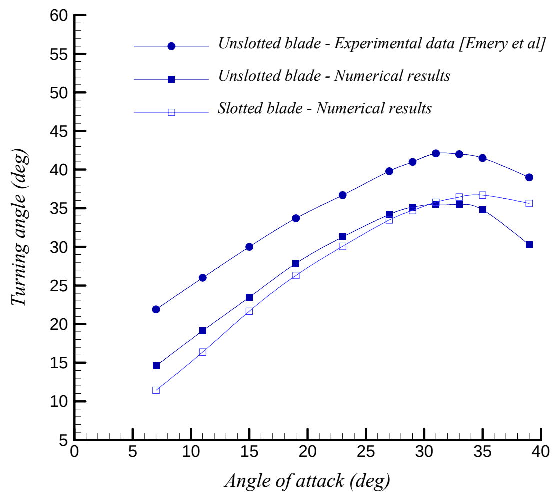


Fig. 16 Variation of turning angle with angles of attack of slotted and unslotted blading

5. Conclusions

In the present study, an attempt has been made to explore numerically the potential of the passive control using slotted blading. The numerical experimentations were performed in the highly loaded linear compressor cascade with NACA 65(18)10. The influences of location, width and slope of the slot were successively analyzed. In the chosen range, the maximum relative reduction of loss coefficient was up to 28.3%, when the slot jet was located approximately halfway between the minimum pressure point and the separation point, the slot width reached the threshold value and the slot slope became less stiff. The results showed that the boundary layer detachment was eliminated and the aerodynamic performance was enhanced for the optimal configuration with acceptable rise in loss coefficients over the range without separation.

Moreover, a difference of about 5^0 between the turning angles with and without slot can be observed. Slot optimal proposed location from previous work has been explained by suction blade boundary layer analysis based on unslotted configuration.

Nevertheless, some other factors, which might to be important for the potential of passive control with slotted blading have not been taken into consideration in the present article, push us to devote further works in order to study the slot convergent form, the number of slots and the spanwise extent in three-dimensional situation.

Nomenclature

C_f	Skin friction coefficient	r_L	Slot leading edge radius [m]
C_p	Static pressure coefficient	t	Thickness at intersection of slot axis and mean Camber line [m]
M	Mach number	y^+	Non dimensional distance
P	Static Pressure [Pa]	W_1	Inlet velocity [m/s]
P_{01}	Inlet stagnation pressure [Pa]	α_1	Angle of attack [^{o}]
R_c	Coanda radius [m]	β_1	Inlet flow angle[^{o}]
R_p	Pressure surface radius [m]	θ	Turning angle [^{o}]
Re	Reynolds number	λ	Stagger angle [^{o}]
S	Relative dynamic pressure	ϖ	Mass averaged total loss coefficient
X	Chordal slot location	σ	Solidity
Y	Slot width [m]	ψ	Angle formed by slot axis and mean camber line [^{o}]
c	Chord length [m]		
r_T	Slot trailing edge radius [m]		

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