Performance Enhancement of a High Turning Axial Compressor Stator Blade Cascade Through End Wall Boundary Layer Suction

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Abstract

Axial flow compressors operate under adverse pressure gradient condition. The growth of boundary layers on blade susfaces and end walls causes increased total pressure loss and flow blockage. This paper presents a method to reduce the pressure loss through suction of low momentum end wall boundary layer in a high Mach number, high turning compressor stator cascade. The end wall suction was applied though slots at discrete chordwise locations near the blade suction surface. CFD simulations were carried out for different slot locations, different suction mass flow rates and at different incidence angles using ANSYS FLUENT software at design inlet Mach number of 0.762. The boundary layer suction technique significantly reduced the total pressure loss across the cascade by reducing the separated flow region at the end wall. The end wall suction slot located at 50-75% blade chord was found to be most effective in reducing the total pressure loss coefficient by 54.6% compared to the baseline case without end wall suction.

Key Words: Transonic Axial Compressor, Boundary Layer Suction, Controlled Diffusion Aerofoil, Total Pressure Loss, Flow separation

1. INTRODUCTION

Owing to high blade loading in transonic axial compressors, the blade and end wall boundary layers tend to separate under off design operating conditions. The aerodynamic blockage contributes to enhanced total pressure loss. It is, therefore, imperative to develop techniques to reduce this flow separation and resulting flow blockage to improve the compressor performance.

Boundary layer suction (BLS) technique to control the growth of boundary layers on compressor end walls and blade surfaces has been investigated by various researchers both in cascades [1-7] and in rotating machines [8-9]. In an attempt to optimize the suction slot location, Chen et al. [1] examined the performance of an axial compressor cascade with spanwise BLS slots on blade suction surface. The optimal slot location was found at 70% blade chord, resulting in a reduction of total pressure loss coefficient, ω, by 27.7% with 1.5% suction mass flow rate at 0^o incidence angle. However, at higher positive incidence angles, the BLS was not effective in reducing the loss. Experimental and numerical studies by Cumpsty et al. [2] on a low-speed compressor cascade showed that BLS reduced ω by 21.9% at 0^o incidence angle. Similar observations are also reported by Guo et al. [3] on the effect of BLS applied to a compressor cascade. Numerical simulations were performed on a low speed aspirated axial compressor cascade with 2mm wide slots at five different chordwise locations on the suction surface. The suction mass flow rate was found to be important and the optimal suction slot location was at 60% chord on the blade suction surface. Numerical investigations by Merchant [5] on boundary layer suction applied to compressor blade suction surface showed that the boundary layer displacement thickness reduced by 10% with increase in suction mass flow rate from 0.5% to 1%. Marty et al. [6] have aslo reported that in a low speed axial compressor cascade the value of ω reduced from 12.58 % without BLS to 8.6% with BLS for a suction mass flow rate of 3.3%. Numerical investigations by Chen et al. [7] on a high speed linear compressor stator cascade showed that chordwise BLS location should contain the region slightly downstream of the onset of the three-dimensional corner separation. With 1% suction mass flow rate, the total pressure loss coefficient, ω, was decreased by 15.2% in the CFD simulations and 9.7% in the measurement under design operating conditions.

Kerrebrock et al.[8] have examined the effect of BLS just prior to shock impingement on the suction surface in an actual compressor with transonic rotor. The aspirated rotor showed improved efficiency and increased stable mass flow range. Experimental and numerical investigations were also carried out by Merchant et al. [9] on axial fan / compressor stages. The suction slots were made on the end wall and on the blade suction surface of an axial fan stage. It is reported that at 95-100% design speed, the BLS was quite effective in removing the low momentum fluid near the blade tip that resulted in delaying the inception of stall.

Published literature on BLS shows a broad mix of experimental and numerical investigations. The effect-tiveness of BLS depends upon the location of suction slot and suction mass flow rate as well. However, most of the research on BLS is found in low Mach number compressor cascades. Also, the suction slots were located on the blade surface making it difficult to implement the scheme in practice, owing to small thickness of the compressor blades. Therefore, in the present study, the effect of BLS to minimize the corner separation and reduce total pressure loss is numerically investigated for chordwise slots near the blade suction surface on the end walls of a linear compressor stator cascade. The results of parametric studies, involving suction slot location, suction mass flow rate and incidence angle, are reported here for a constant inlet Mach number of 0.762.

2. TEST CASCADE

The numerical studies were carried out on a high turning (43.7°) linear cascade corresponding to mean section of a compressor stator with controlled diffusion aerofoils (CDA). The geometric data of the stator blade and the design flow conditions are given in Table 1 and Table 2 respectively (Kamble [10]).

Table 1 Geometric specifications of cascade

Parameter	Symbol	Value	Units
Blade Chord	C	72.3	mm
Blade Pitch	S	55.07	mm
Blade Solidity	σ	1.25	-
Aspect Ratio	AR	2.12	-
Inlet Metal Angle	α_{1m}	45.7	deg
Outlet Metal Angle	α_{2m}	-4	deg
Stagger Angle	γ	16.7	deg

Table 2 Design flow conditions

Parameter	Symbol	Value	Units
Inlet Mach No.	M_{in}	0.762	-
Inlet Flow Angle	α_1	43.7	deg
Outlet Flow Angle	α_2	0	deg
Design Incidence Angle	i	-2	deg

3. COMPUTATIONAL MODEL AND SOLVER SETTINGS

Figure 1 shows the geometric model of computational domain generated using ANSYS ICEMCFD software. The boundary conditions applied are also indicated. The computational domain extended one chord upstream and two chords downstream of the blade leading and trailing ends respectively.

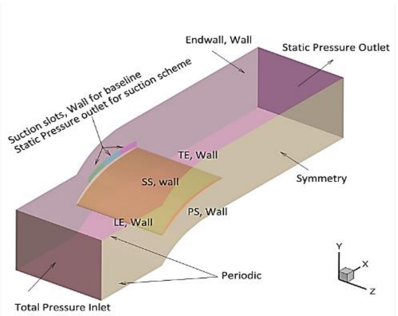

Fig.1 Cascade geometry and boundary conditions

The suction slot geometry and its position on the endwall were selected based on initial studies on the baseline cascade. Figure 2 shows the suction slot layout on the endwall. Figure 3 shows the structured computational grid, wherein 'O' grid is placed around the airfoil and 'H-O-H' grid in the rest of the domain. To resolve boundary layer flow, the y^+ value was maintained < 5.

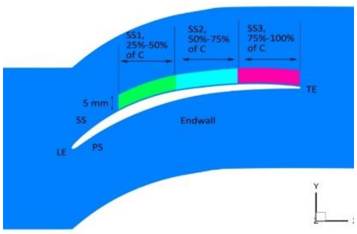

Fig.2 Location of suction slots

Numerical simulations were carried out using ANSYS FLUENT software. Density based solver was chosen for solving the RANS equation, invoking the energy equation. The turbulence model used was eddy viscosity based two-equation SST *k-ω*. The flow medium was air at sea level inlet conditions. The computations were carried out at the design inlet Mach number of 0.762. The convergence criterion was set to a minimum residual level of 10^{-5}.

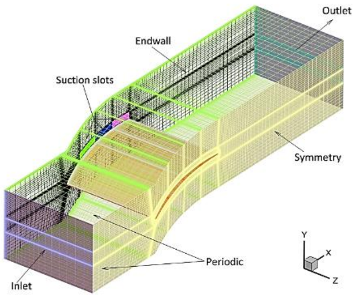

Fig.3 Computational grid

4. GRID INDEPENDECE STUDY AND VALIDATION

A grid independence study was carried out using four computational grids of 5.1 lakh, 9.1 lakh, 11.5 lakh and 15.5 lakh cells respectively. The mass averaged total pressure loss coefficient at 25% chord from the blade trailing end is plotted for different grids, as shown in Fig.4. It indicates that a grid of ~11.5 lakh cells is sufficient for subsequent computations.

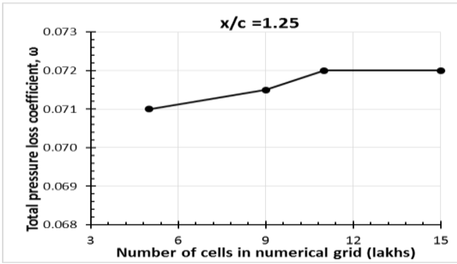

Fig.4 Grid independence study

Figure 5 shows that the numerical prediction of blade surface Mach number at 50% span agrees well with the experimental data. This shows that the numerical modelling is satisfactory for detailed study.

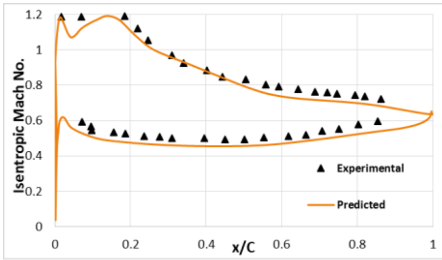

Fig. 5 Isentropic surface Mach number distribution on blade at mid-span under design conditions

5. RESULTS AND DISCUSSION

5.1 Flow through Baseline Cascade

Initial numerical studies were carried out on the baseline cascade at design inlet Mach number and incidence angles ranging from -12° to +8°, in steps of

2º. The flow behaviour is examined at three planes, *viz.* a streamwise Plane A at 25% chord downstream of TE, and two spanwise Planes B and C, at z/c=0.05 and z/c=0.5 respectively. Figure 6 shows that the minimum value of ω occurs at i = -4º. On either side of this incidence angle, the loss increases, with higher rate of increase at positive incidences. The blade is susceptible to stall at i = +6º, where ω is twice the minimum value.

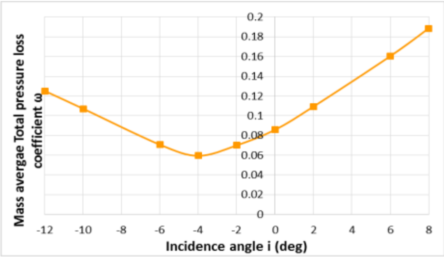

Fig.6 Total pressure loss coefficient at streamwise Plane-A

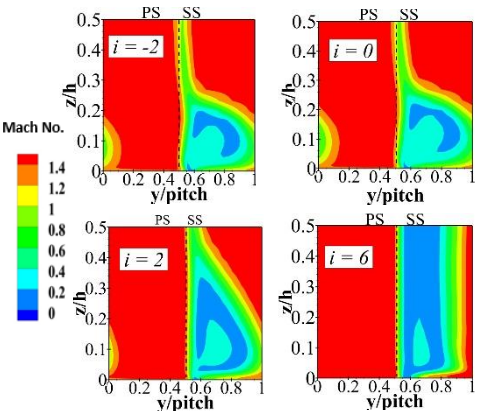

Fig. 7 Mach number distribution on streamwise Plane-A at different incidence angles

Figure 7 shows that even at design incidence angle of -2º, the flow near the end wall has strong recirculation. As the incidence angle increases, the recirculation region, and hence the total pressure loss, increases. At i = +6º (near stall condition), the entire suction side of the flow passage is covered with low momentum fluid owing to flow separation along the complete blade span.

Figure 8 shows that at a design incidence angle of -2º, the flow separation at Plane-B (z/h=0.05) initiates at 50% chord and the separated region extends to almost full pitch as the flow proceeds downstream. At i=0º, the separation initiation point shifts upstream and the flow separation zone grows pitchwise. At higher incidence angles of +2º and +6º, the separation initiation point continues to move upstream, but the pitchwise extent of the separated region shrinks. At Plane-C (z/h=0.5), there is no flow separation from i = -2º to i = +2º. However, at stall incidence angle of i= +6º, the flow separates on the suction surface even at midspan and the extent of separated flow zone is similar to that at z/c=0.05, as is evident from Fig.7 also.

5.2 Effect of end wall suction

The locations of suction slots on the end wall near the suction surface of the blade were chosen based on the flow characteristics of the base line cascade. It is logical to activate the suction at a point upstream of the separation initiation point and extending up to the trailing end. The suction was arranged through three slots: 25% to 50% chord (SS-1), 50% to 75% chord (SS-2) and 75% to 100% chord (SS-3), as shown in Fig. 2. The pitchwise width of each slot was 5mm. The suction mass flow rate (m_{suc}) was varied from 1% to 1.75% of primary mass flow rate.

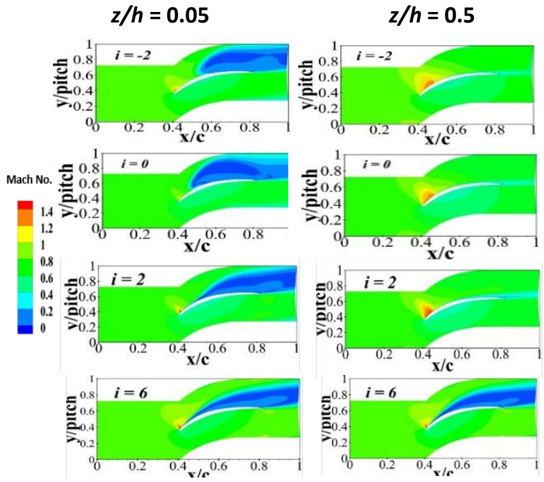

Fig. 8 Mach number distribution on pitchwise Plane-B and C at different incidence angles

Initial simulations with SS-1 showed that this slot location was ineffective in suppressing the end wall separation at all suction mass flow rates. But, the SS-2 and SS-3 slots were quite effective. Hence, the following discussion is focused on the results obtained with SS-2 and SS-3 slots only.

Figure 9 shows that SS-3 reduces ω to 0.062 at m_{suc}=1.75%; however, SS-2 is more effective in reducing ω to 0.033 at a lower m_{suc} of 1.25 %. For slot SS-2, ω drops sharply as m_{suc} is increased from 1% and becomes minimum at m_{suc}=1.25%. At higher m_{suc}, there is a gradual increase in ω to a value of 0.028, which is much lower than the value for SS-3 slot. The increase in ω for SS-2 at higher m_{suc} may be due to redistribution of flow in the forward part of the suction surface so as to increase ω. Shifting SS2 by 10% blade chord upstream towards LE did not benefit the loss reduction. Similarly, shifting SS-2 10% chord downstream gave results comparable to SS-3.

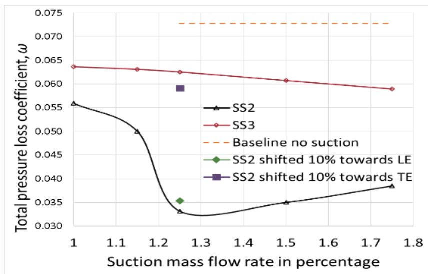

Fig.9 Variation of ω with m_{suc} at i = -2º

Figure 10 shows the effectiveness of SS-2 compared to SS-3 in improving the end wall flow field, resulting in reduction of ω at all m_{suc}. The contours of Mach number on Plane-A for baseline cascade without end wall suction and with 1.25% suction using SS-2 and SS-3 slots are shown in Fig.11. While the reduction in vortex core with SS-3 is not significant, the SS-2 is able to remove the low momentum fluid from the end wall, thus improving the flow quality throughout the blade span with substantial reduction in ω. Also, as can be seen from Fig.12, the suction through slot SS-2 is capable of removing the low momentum fluid from the entire chordwise length of the blade. The flow near the end wall is almost same as in the core flow region, for example at the midspan (Plane-C). In comparison, the suction through SS-3 is much less effective and the low momentum fluid continues to occupy a large part of the blade passage right from 50% chord to TE.

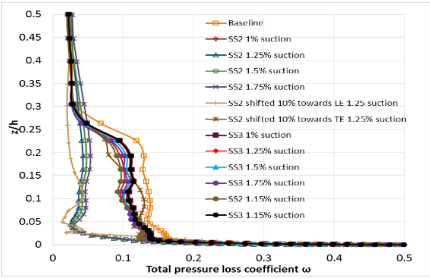

Fig.10 Total pressure loss coefficient along the span at streamwise Plane-A

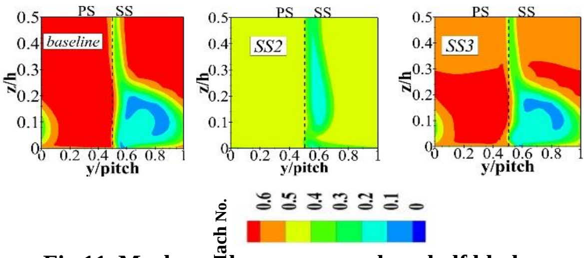

Fig.11 Mach number contours along half blade span on streamwise Plane-A, m_{suc} = 1.25 %

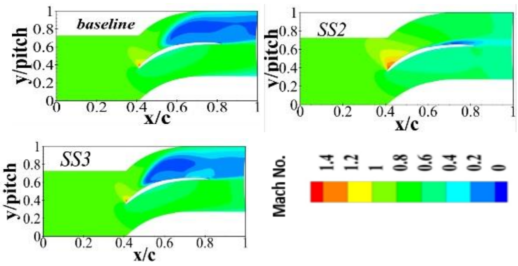

Fig.12 Mach number contours on pitchwise Plane-B at z/h=0.05, m_{suc} = 1.25 %

6. CONCLUSION

Boundary layer suction (BLS) technique has been investigated to improve the aerodynamic performance of a highly loaded compressor stator cascade. Numerical investigations were carried out to analyze the effect of parameters like position of suction slots and suction mass flow rate at design incidence angle only. Results have shown the effectiveness of BLS in reducing the endwall separation and associated losses. The main conclusions drawn from the present study are:

- The effectiveness of suction scheme depends on the location of suction slot and incidence angle
- Total pressure loss decreases with increase in suction mass flow rate
- SS1 and SS3 slots are found to be less effective in reducing the total pressure loss
- SS2 slot with 1.25% suction mass flow rate reduces ω by 54.46%
- Shifting the SS2 slot 10% towards LE results in reduction of total pressure loss by 51%, but shifting the SS2 slot 10% chord towards TE proves to be ineffective and the results are almost close to SS3 slot configuration
- Overall, the boundary layer suction proves to be a promising technique in reducing the total pressure loss. Among all the suction slot configurations tested, the SS2 with its length extending from 50% to 75% blade chord is found to be most effective in terms of maximum reduction in ω with a suction mass flow rate of 1.25% of the passage mass flow rate

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