A parametric investigation of endwall vortex generator jet on the secondary flow control for a high turning compressor cascade

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Abstract
A parametric investigation of secondary flow control using endwall vortex generator jet (VGJ) is performed in a high turning compressor cascade. The mechanisms for the variations of VGJ performance with different jet parameters including the pitch angle, yaw angle and jet-to-inflow total pressure ratio are discussed in detail. And then the potential of VGJ at the off-design points is further validated. The results show that the influence of VGJ on the cascade performance depends on the combination of the loss increase in the upwash region and the loss reduction in the corner region. A jet pointing upstream of the cascade or with too large jet-to-inflow total pressure ratio would enhance the mixing losses in the upwash region remarkably. Whereas a jet with negative yaw angle, too large or too small pitch angle would reduce the effects of VGJ on the endwall cross flow and the low energy fluid accumulation in the corner region due to the weakened reverse vortex. In this work, the optimal performance is obtained by the jet with a pitch angle of 20° and a yaw angle of 0°. For the off-design points, the potential of VGJ on the loss reduction is enhanced with the increase of the incidence. The loss reductions at \( i=5° \) and \( i=5° \) are 13.2% and 32.5% respectively, whereas the beneficial effect on the flow turning decreases slightly.

Key words: Compressor cascade, Parametric investigation, Vortex generator jet, Secondary flow, Loss reduction

1 Introduction

A jet issuing from the hole pitched and skewed with respect to the main flow could generate streamwise vortices to enhance the fluid exchange between the boundary layer and the main flow. This technique is known as the vortex generator jet (VGJ) for flow control (Compton et al., 1992). Compared with the solid vortex generator (VG), the VGJ is active flow control technique, which has the advantages of effectiveness, controllability and low cost. Moreover, less or even no additional loss is produced while the VGJ is turned off. Therefore, it has been widely applied to the control of separation for the external flow over the aircraft and missile (Johnston et al., 1990, Kourta et al., 2006, Scholz et al., 2008, Prince et al., 2009 and Scholz et al., 2010), which successfully obtains the benefits of increasing the lift-to-drag ratio and stall angle.

Recently, the VGJ is further introduced to the internal flow control in the turbo-machinery. Gompertz et al. (2009), Memory et al. (2010), Zander et al. (2011) and Gmelin et al. (2012) performed systematical investigation of boundary layer separation using VGJ in the low-speed turbine and highly loaded linear compressor cascade, respectively. The results show that both the steady and unsteady VGJ on the suction side could delay or even eliminate the boundary layer separation effectively. A wake loss reduction up to 35% is obtained by Gompertz et al. (2009), and the maximum loss reduction is 13% by Gmelin et al. (2012). Moreover, it is suggested that the unsteady VGJ provides a comparable even better effect to the steady VGJ with less jet mass flow rate. Zheng et al. (2006) reported a maximum loss reduction of 22.8% in a high-speed linear compressor cascade. It is recommended that the optimal excitation location is just upstream the separation point. However, the disadvantage of VGJ on the suction side is that the implementation of complex air supply pipes inside the blade is strictly limited by the small blade thickness, as shown by Evans and Hodson (2012). Therefore, in order to enhance the practical potential of VGJ application in the compressor, Feng et al. (2015) and Liu et al. (2016) proposed the concept of endwall VGJ located upstream the leading edge to control the
endwall secondary flow. It is shown that the transverse migration of the endwall boundary layer could be well suppressed by the induced vortex. As a result, the low energy fluid accumulation in the corner region is weakened and the separation is delayed remarkably. The loss reductions on the cascades with an inlet Mach number of 0.23 and 0.67 are up to 9.5% and 12.9% respectively, whereas the jet-to-mainstream mass flow ratio is less than 0.5%, which validates the high efficiency of this method.

In contrast to the extensive investigations about the benefits of the jet on the cascade loss reduction, the mechanisms for the variations of VGJ performance with different jet parameters are still not well understood. Therefore, this work is aimed to investigate the detailed flow structure and loss behaviors for different pitch angle, yaw angle and total pressure of the jet. Especially, in order to better understand the interaction mechanisms between the jet and the secondary flow, the comparisons are particularly focused on the intensity of vortices and the change of resulting losses in the near endwall region, by which it is expected to obtain a conclusive recommendation for the optimal parameters of VGJ. Then, the potential of VGJ in a range of incidences from -5° to 5° is further validated.

2 Vortex generator jet and numerical methods

2.1 Geometrical description

A high turning linear compressor stator cascade with a camber angle of 60° is used in the numerical investigations. This cascade is designed by Song et al. (2007) and Chen (2009) for the investigation of flow control in the highly loaded compressor environment. More information about the cascade is given in Tab. 1.

| Table 1 Cascade parameters |
|----------------------------|
| Axial chord (B)            | 120 mm          |
| Blade height (H)           | 100 mm          |
| Pitch (t) (mm)             | 94 mm           |
| Camber angle (θ)           | 60°             |
| Inlet flow angle           | 48°             |
| Reynolds number            | 6.7×10^5        |

Fig. 1 Schematic of VGJ in the cascade

Figure 1 shows the isolated vortex generator jet (VGJ) arrangement and the definition of angles with respect to the endwall. The jet outlet is located at a chord length of x/B=−10% upstream of the leading edge with a diameter of 5mm. The pitchwise distance from the suction side is y/t=10%. The jet direction is defined by the pitch angle (α) and the yaw angle (β), where α is the angle between the jet center line and the endwall; β is the angle of the projection against the pitchwise direction. A yaw angle of zero degree is defined as the pitchwise direction. The positive and negative yaw angles correspond to the jet pointing upstream and downstream, respectively. Additionally, since the jet is usually issued from the hole inside the casing in the real compressor, a jet pipe with a length of 20 mm bellow the endwall is considered in the work. As a result, the velocity profile at jet exit, which is exactly nonuniform, is determined by the pressure difference between the pipe’s inlet and exit.

2.2 Numerical method validation

The three-dimensional steady viscous Reynolds-averaged Navier-Stokes equations are solved by using the commercial CFD package ANSYS14.0-CFX. To evaluated the performance of the turbulence model on simulating the severe separation in the high turning compressor cascade, five different turbulence models are tested and validated against the experimental data for the baseline case with an incidence of i=0°. They are standard k-ε, RNG k-ε, shear stress transport (SST), k-ω and BSL. For the standard k-ε and RNG k-ε model, the scalable wall function is utilized to
simulate the near wall flow field. In comparison to the standard wall function, it can be applied to any arbitrary fine mesh, regardless of the size of the cells close to the wall, thus increasing the robustness and accuracy of the turbulence model (Sultan et al., 2016). The automatic wall treatment, which allows a gradual switch between wall functions and low-Reynolds number grids, is used for the other turbulence models. The schematic of the computation grid is shown in Fig. 2, where the hexahedral mesh is used. Since the turbulence models have specific requirements for the near wall mesh spacing, different grids are prepared correspondingly. The total number of the computational grids and the dimensionless distance of the first cell from the wall are shown in Tab. 2.

| Turbulence models          | Number of grids | First node near the wall |
|----------------------------|-----------------|--------------------------|
| Standard k-ε, RNG k-ε     | 900000          | Y+=30~60                 |
| SST, k-ω and BSL         | 1400000         | Y+<1                     |

In order to account for the incoming boundary layer, the span-wise profile of the total pressure tested by Chen (2009) is imposed to the inlet of the computational domain. The mass-averaged total pressure is 103825Pa and the Mach number is about 0.23. The axial chord Reynolds number is 6.7×10^5. The total temperature at the cascade inlet is 300K. The incoming flow turbulent intensity and eddy viscosity ratio are 2% and 10, respectively. An average static pressure of 101325Pa and radial equilibrium are used at the outlet located at 200% chord downstream the trailing edge. Due to the symmetry of the flow field, the boundary condition of symmetrical plane is applied at the midspan. The endwall and the blade surface are adiabatic.

The pitch-averaged total pressure loss along the blade height for the baseline case with an incidence of i=0° is shown in Fig. 3. The most obvious differences are observed in the region from z/H=10% to 25%. Among these turbulence models, the results provided by the standard k-ε model agree well with the experimental data, whereas the k-ω model overestimates the value of the losses and the SST model presents the smallest losses. The total loss coefficient at the outlet predicted by the standard k-ε model is 0.0675, obtaining a negligible discrepancy with respect to 0.0678 in the experiment.

Figure 4 provides the limiting streamlines on the suction side. The scope and the start line of the separation region predicted by the numerical simulation using standard k-ε model agree well with the experimental result. However, slight difference in the separation region is detected. As is presented by Chen et al. (2014) and Zhang et al. (2014), almost no Reynolds-Averaged turbulence model could supply identical details in the separation region as the experimental results for the high turning compressor cascade. Therefore, the flow field predicted in this work is acceptable.
Figure 5 further presents the contour of the static pressure coefficient on the endwall. The low and high pressure regions are well simulated. Slight difference between the numerical and experimental results is observed near the leading edge, where the reliability of the experimental data should be considered seriously. As the inflow impacts the leading edge, the pressure changes drastically with sharp gradient. The sparse measurement holes utilized in the experiment (Chen, 2009) can’t provide accurate contour of static pressure in this region. Therefore the pressure contour tested in the experiment is more reliable in the region with moderate pressure gradient, where the numerical results agree with experimental data.

Overall, it could be concluded that the standard $k$-$\varepsilon$ model is superior to the others by reaching the closest results to the experiment, which enables to quantify the influence of VGJ on the cascade performance with a reasonable accuracy.

3 Results and discussions

3.1 Impact of VGJ orientation

As is known, one of the most important parameters dominating the performance of VGJ is the jet orientation with respect to the incoming flow. Hence, a parametric study of the pitch angle ($\alpha=10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$) and yaw angle ($\beta=-30^\circ$, $-20^\circ$, $-10^\circ$, $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$) is performed to check the effects of the jet direction on the performance of VGJ. Concerning the application of VGJ in the real compressor, one of the most practicable methods to generate the jet is inducing the air from the downstream higher pressure stage, it is more reasonable to impose the total pressure rather than the velocity at the jet inlet. Therefore, a constant total pressure of 104825 Pa, which is slightly higher than that at the cascade inlet, is fixed at jet inlet. The resulting jet-to-inflow velocity ratio is approximately 1.2.

To take an account of the mass and the kinetic energy of the jet, the total pressure loss coefficient is calculated by Eq. (1).
\[ \omega = \frac{(m_0 P_0^* + m_j P_j^*) - (m_0 + m_j) P_j^*}{m_0 (P_0^* - P_0) + m_j (P_j^* - P_j)} \]  

(1)

Where \( m \) is the mass flow rate, \( P^* \) and \( P \) are the mass-averaged total pressure and mass-averaged static pressure, respectively. The subscript “0” and “1” represent the inlet and the outlet of the cascade, and the subscript “j” represents the inlet of the jet.

The loss reduction ratio relative to the baseline case is defined as

\[ \sigma = \frac{\omega_{ori} - \omega}{\omega_{ori}} \]  

(2)

Figure 6 and 7 show the influence of the jet orientation on the total pressure loss coefficient at the cascade outlet. Figure 6 and 7 imply that the performance of VGJ is more sensitive to the yaw angle than to the pitch angle. While the yaw angle is \( \beta=0^\circ \) in Fig. 6, the loss reduction does not change too much from \( \alpha=10^\circ \) to \( 40^\circ \). However, with the increase of yaw angle from \( \beta=-30^\circ \) to \( 40^\circ \), the loss decreases sharply at first and then increases slowly (as shown in Fig. 7). A maximum loss reduction up to 28.4% relative to the baseline case is provided by the VGJ with a pitch angle of \( \alpha=20^\circ \) and a yaw angle of \( \beta=0^\circ \). In external flow field, it has been concluded that the VGJ with the pitch angle ranging from \( 15^\circ \) to \( 45^\circ \) and the skew angle between \( 45^\circ \) and \( 90^\circ \) could obtain the optimal benefit on vortex generation and separation control, as shown by Zhang et al. (2014) and Stillfried et al. (2012). Therefore, the similar tendency is observed in this work, where an optimal yaw angle of \( \beta=0^\circ \) corresponds to a skew angle of \( 48^\circ \) against the inflow.

In order to better understand the effect mechanisms of VGJ on the secondary flow, Fig. 8 presents the axial vorticity at the sections of \( x/B=-5\% , \ 20\% , \ 60\% \ \text{and} \ 120\% \ \text{in the passage}. \) The intensity of vorticity is calculated by \( \Omega = \frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z} \). With the application of VGJ, a dominant reverse vortex (RV) opposite to the passage vortex (PV) is generated downstream of the jet. This vortex could transport the low energy fluid to the mainstream in the upwash region, thus constraining the endwall cross flow. While in the downwash region near the suction side, the fluid of the mainstream is swept to the endwall to reenergize the boundary layer. Then the ability against the transverse pressure gradient and the streamwise adverse pressure gradient is enhanced, which will be further discussed later. Owing to the combined effects, the low energy fluid accumulation in the corner region is diminished and the boundary layer separation on the suction side is weakened. However, the unfavorable impact of the VGJ is also detected in the upwash region, where the losses are increased by the mixing between the mainstream and the low energy fluid, as shown in Fig. 9. Therefore, the total effect of VGJ on the cascade performance depends on the combination of the above two loss behaviors.

Furthermore, the streamlines and the vorticity give a good impression of the development of RV. Generally, while the RV travels downstream, the low energy fluid is drawn into the vortex core. As a result, the RV expands and the
vorticity is weakened rapidly by the mixing processes. Due to the transverse pressure gradient and the pitchwise migration of endwall boundary layer, the RV is deflected toward the suction side. At the rear part of the passage, the RV is dissipated completely, and then the jet fluid is involved in the passage vortex.

In addition, Fig. 8 (b) ~ (d) illustrate the effects of pitch angle on the VGJ performance. At the sections of \(x/B = -5\%\) and 20\% near the leading edge, a RV closer to the endwall with wider region of high vorticity is observed for the case with a pitch angle of \(\alpha = 10\^\circ\) in comparison to those with larger pitch angles in Fig. 8 (c) and (d). Whereas at the section of \(x/B = 60\%\), a weaker RV is visible for \(\alpha = 10\^\circ\) than the other cases. Therefore, it could be concluded that the decrease in pitch angle results in an increase in wall shear stress below the jet, thus dissipating the RV more rapidly. With an increased pitch angle of \(\alpha = 40\^\circ\) in Fig. 8 (d), the decreased tangential velocity component of the jet result in a smaller RV compared with that in Fig. 8 (c), which is displaced closer to the suction side and decays rapidly in the rear part of the passage. Hence the losses in the corner region are only changed slightly compared with the baseline case, as shown in Fig. 9 (a) and (d).

From Fig. 8(c), (e) and (f), it is visible that the vorticity is strengthened with the increase of the yaw angle. The strongest and weakest vortex are generated by the VGJs with \(\beta = 40\^\circ\) and \(-30\^\circ\), respectively. A strong vortex would lead to significant mixing losses in the upwash region (as shown in Fig. 9(e)), which in turn reduces the performance of the VGJ on the loss reduction. Conversely, a weak RV (as shown in Fig. 8(f)) decays rapidly along the streamwise direction and almost entirely loses its effect on the endwall secondary flow as well as the low energy fluid accumulation in the corner region in the rear part of the passage. Therefore, the vortex with moderate strength generated by the VGJ with a pitch angle of \(\alpha = 20\^\circ\) and a yaw angle of \(\beta = 0\^\circ\) obtains the best performance on the loss reduction, as shown by the comparisons of losses in Fig. 9 (c), (e) and (f).

![Omega_x](https://via.placeholder.com/150)

\[\Omega_x(\text{s}^{-1}) : -9000-7872-6744-5615-4487-3359-2231-1103 \quad 26 \quad 1154\]

(a) Baseline case  
(b) \(\alpha = 10\^\circ, \beta = 0\^\circ\)  
(c) \(\alpha = 20\^\circ, \beta = 0\^\circ\)  
(d) \(\alpha = 40\^\circ, \beta = 0\^\circ\)  
(e) \(\alpha = 20\^\circ, \beta = 40\^\circ\)  
(f) \(\alpha = 20\^\circ, \beta = -30\^\circ\)

Fig. 8 Axial vorticities in the passage with different pitch angles and yaw angles
For a better understanding of the VGJ effect on the cascade performance, the comparisons of the pitch-averaged total pressure loss along the blade height are presented in Fig. 10 and 11. According to the loss changes by using VGJ compared with the baseline case, the pitch-averaged total pressure loss along the blade could be divided into four regions from the endwall to the midspan. In region 1, the fluid exchange near the endwall contributes to a slight loss decrease. However, the losses in region 2 increase compared with the baseline case, which is attributed to the mixing processes in the upwash region. In region 3 (approximately from $z/H=10\%$ to $30\%$), significant loss reductions are obtained, which is resulted from the reduction of low energy fluid accumulation in the corner region. The losses in the near midspan region of $z/H=30\%$ to $50\%$ (denoted as Region 4) are almost unchanged. Overall, the best performance of VGJ on loss reduction is obtained in the case of $\alpha=20^\circ$ and $\beta=0^\circ$, as discussed in Fig. 8 and 9.
Figure 12 depicts the limiting streamlines and the static pressure coefficient on the suction side and the endwall for the baseline case and the controlled case with $\alpha=20^\circ$ and $\beta=0^\circ$. The streamlines are plotted using the tangential velocity components on the first nodes near the wall. And the static pressure coefficient is defined as the difference of the local static pressure $P$ and the inlet static pressure $P_0$ to the inlet dynamic pressure $q_0$: $C_p=(P-P_0)/q_0$. It could be observed that the secondary flow topology on the endwall is changed distinctly by using VGJ. The limiting streamlines near the jet exit are bent to the pitchwise direction due to the additional tangential momentum inputted. Thus the ability of the fluid withstanding the transverse pressure gradient is enhanced. This can be concluded as another effect mechanism of VGJ on the secondary flow. Downstream of the jet, an obvious separation line is observed, which indicates that the low energy fluid here is transported away from the endwall. As a result, the cross flow is suppressed effectively and the low energy fluid accumulation in the corner region is weakened significantly. Due to the transverse pressure gradient, the separation line on the endwall is deflected and ultimately intersects with the suction side near the trailing edge. As the endwall secondary flow is controlled by using VGJ, the separation line on the suction side is shifted downstream and then the blockage is weakened, contributing to higher pressure rise in comparison to the baseline case, as predicted by the contour of static pressure coefficient near the trailing edge.

Moreover, the comparison of static pressure coefficient at $z/H=10\%$ of the blade height in Fig.13 also shows that the blade loading is increased significantly by using VGJ. The pressure of the pressure side is almost unchanged except the near trailing region. Whereas on the suction side, since the boundary layer in the corner region is reenergized by the fluid swept from the mainstream (as earlier discussed in Fig. 8), the pressure for the zone, which is approximately from the leading edge to $x/B=75\%$ of chord length, is reduced obviously. Owning to the weakened boundary layer separation in the rear part of the passage, as previously shown in Fig. 12, the static pressure coefficient near the trailing edge is consequently increased.
3.2 Impact of jet total pressure

Another main parameter influencing the performance of VGJ considered in this work is the total pressure of the jet. The sensitivity of VGJ performance with different jet-to-inflow total pressure ratio is shown in Fig. 14. In general, with increasing total pressure applied at the jet inlet, a continuous decreasing total pressure loss at the cascade outlet can be observed. The loss declines sharply for $P_j^*/P_0^* < 1.01$ and slowly for $P_j^*/P_0^* > 1.01$. When a jet-to-inflow total pressure ratio of $P_j^*/P_0^* = 1.039$ is applied, the total pressure loss is reduced by 29.5% compared with the baseline case. Especially, when the total pressure ratio is $P_j^*/P_0^* = 1.0$, a considerable loss reduction of 21.8% is gained. It indicates that in the practical system, the air of the jet could be induced from the nearest upstream or downstream cascade, which could shorten the air-supply pipes. Moreover, even no complex pump systems are required. Hence, the possibilities of application and manufacture are enhanced.

Figure 15 illustrates the jet-to-inflow mass flow ratio. It is noticeable that the mass flow ratio increases linearly with the total pressure ratio. Furthermore, the mass flow rate is less than 0.5% of the inflow, while an appreciable loss reduction more than 20% can be achieved, which confirms the effectiveness and efficiency of the VGJ on the endwall secondary control and loss reduction.

![Fig. 14 Total pressure loss with different jet total pressure](image1)

![Fig. 15 Mass flow ratio with different jet total pressure](image2)

![Fig. 16 Axial vorticities with different jet-to-inflow total pressure ratio](image3)
Figure 16 shows that with the increase of the jet total pressure, a stronger reverse vortex is induced and the deflection of the jet fluid (Represented by the black 3D streamlines) in the rear part of the passage is reduced. As a result, the low energy fluid accumulation in the corner region is weakened. Nevertheless, the mixing losses in the upwash region are strengthened (as shown in Fig. 17), so the total loss does not decrease too much for $P_j^*/P_0^* > 1.01$.

### 3.3 Performance of VGJ at off-design points

Further comparisons of the total pressure loss at the cascade outlet for the incidences ranging from $i=-5^\circ$ to $+5^\circ$ between the cases with and without VGJ are shown in Fig. 18. Based on the above investigations, the pitch angle and the yaw angle are fixed at $\alpha=20^\circ$ and $\beta=0^\circ$ in this part. It is obvious that the application of VGJ provides a benefit of loss reduction over the entire operation range. Moreover, with the increase of the incoming incidence, the ability of VGJ to improve the cascade performance is enhanced. At $i=-5^\circ$, a relative total pressure loss reduction of 13.2\% is obtained. While a loss reduction up to 32.5\% is predicted at $i=+5^\circ$.

The distribution of exit flow angle is illustrated in Fig. 19. Generally, over the entire operation range, the flow turning is enhanced compared with the baseline case with the same incidence, which indicates that the load is increased. This effect decreases slightly with the increase of the incidence. The increase of the exit flow angle is 1° at the incidence of $i=-5^\circ$, whereas it is 0.8° at the near stall point $i=+5^\circ$. 

![Fig. 17 Total pressure losses with different jet-to-inflow total pressure ratio](image)

![Fig. 18 Total loss at the outlet for different incidences](image)

![Fig. 19 Exit flow angle for different incidences](image)
4 Conclusions

A parametric investigation of secondary flow control using endwall vortex generator jet (VGJ) is performed in a high turning compressor cascade with a camber angle of 60°. The results indicate that:

The endwall VGJ could reduce the secondary flow losses by increasing the tangential velocity component opposite to cross flow near the jet exit, enhancing the fluid exchange between the boundary layer and the mainstream as well as suppressing the traverse migration of the passage vortex.

The VGJ performance depends on the intensity of the reverse vortex opposite to the passage vortex. Excessively strong RV generated by the jet pointing to upstream would increase the mixing losses in the upwash region remarkably. The jet with negative yaw angle or too large pitch angle would weaken the RV and reduce the effect of the VGJ on suppressing the secondary flow. Additionally, the RV induced by the jet with a too small pitch angle would lead to severe wall shear stress, thus dissipating the RV more rapidly. The VGJ with a pitch angle of 20° and a yaw angle of 0° performs best for the separation control and loss reduction in this work.

Even with same total pressure as that at the cascade inlet, a loss reduction of 21.5% is achieved. With the increase of the jet-to-inflow total pressure ratio, the loss decreases sharply for $P_j^*/P_0^* < 1.01$. However, a higher jet total pressure would produce a stronger reverse vortex, increasing the mixing losses in the upwash region. Therefore the loss reduction doesn’t change too much for $P_j^*/P_0^* > 1.01$

Furthermore, the VGJ could obtain significant loss reduction and loading enhancement for the incidence ranging from $i=-5°$ to $+5°$. With the increase of the incidence, the effect of VGJ on the cascade performance is enhanced. The relative loss reductions for $i=-5°$ and $+5°$ are 13.2% and 32.5% respectively, whereas the jet-to-inflow mass flow ratio is less than 0.5%, thus validating the high efficiency of VGJ.

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