LARGE EDDY SIMULATION OF CORNER STALL CONTROL IN A LINEAR COMPRESSOR CASCADE BY BLENDED BLADE AND ENDWALL TECHNIQUE

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ABSTRACT

Under the influence of a strong adverse pressure gradient, secondary flow, and other factors, compressor cascades are prone to corner separation, and even leading to corner stall, which seriously affects aerodynamic performance. In this paper, large eddy simulation is used to investigate the effects and mechanisms of corner stall controlled by the blended blade and endwall technique. The suction side root of a modified NACA65 blade is designed by this technique. The results show that the corner stall topology is changed, in which a single large separation vortex on the endwall is weakened and broken into two small separation vortices, and the spanwise and pitchwise ranges of corner separation are reduced. Most importantly, the total pressure loss coefficient is reduced compared with the prototype cascade. All above prove that the blended blade and endwall technique can control corner stall in the compressor cascade to a certain extent. The underlying physical mechanisms are as follows: by increasing the dihedral angle, the intersection of the boundary layers and the development of the corner vortex are obviously suppressed. Moreover, the axial and spanwise forces generated by the technique can increase the kinetic energy of the surrounding fluid and transport the low-energy fluid upward to reduce accumulation on the endwall respectively.

Keywords: Compressor Cascade; Blended Blade and End Wall; Corner Stall; Large Eddy Simulation

INTRODUCTION

The Compressor is the core component of an aeroengine, and the development of high-efficiency and high-load compressors is the key to improving aeroengine performance. However, to pursue high loads, the adverse pressure gradient in the compressor blade passage must also be enhanced. Under the mutual influence of factors such as the strong adverse pressure gradient, pitchwise pressure difference and intersection of boundary layers, corner separation readily occurs. When the aerodynamic load increasing to a certain value, separated and reverse flow will appear at the suction side and the endwall of the compressor cascade, leading to the corner stall [1], which will cause severe aerodynamic blockage in the passage, and a sharp increase in loss, and will seriously affect the efficiency of the compressor. Consequently, to improve the aerodynamic performance of compressors, it is important to obtain a deeper understanding of corner stall and develop effective control methods to weaken this phenomenon.

Methods for flow control in the corner region of a compressor cascade can be divided mainly into active and passive control methods. Examples of active control methods are boundary layer suction and blowing, while examples of the passive methods are non-axisymmetric endwalls and vortex generators. The blended blade and endwall (BBEW) technique employed in this paper is a passive control method that improves the corner flow by changing the geometry of intersection between the hub and the blade. In 1963, Smith et al. [2] gave a strict definition of the dihedral angle, which is
the key parameter describing the geometry of the corner. In 1980, Debruge [3] presented a theoretical study on the effect of fillet radius on the aerodynamic performance of turbocompressors and pointed out that the appropriate fillet radius of the transition between blade and endwall can prevent corner separation. Ji et al. [4] then proposed an equivalent two-dimensional corner boundary layer model and noted that the corner separation can be eliminated or reduced by increasing the dihedral angle or decreasing its streamwise gradient within the boundary layer scale. In 2012, Ji et al. [5] proposed the BBEW technique, which connects the blade and the endwall with different radii of curvature in the boundary layer scale and controls corner separation by adjusting the distribution of dihedral angle along the streamwise direction. Ji et al. [6] and Yi et al. [7] took axial compressors and centrifugal compressors as examples to explore the application of the BBEW technique. Li et al. [8] experimentally verified that the BBEW technique could effectively reduce corner separation and further studied the physical basis of the technique. By combining the BBEW technique with the nonaxisymmetric endwall technique, Meng et al. [9] proposed the Full-BBEW, which significantly reduced the aerodynamic blockage in a compressor cascade.

In conclusion, the above numerical simulations have mostly been based on Reynolds-averaged Navier-Stokes (RANS) method to explore the effects and physical mechanisms of the BBEW technique on corner separation, but there is a lack of in-depth discussion focusing on the application of the BBEW technique in corner stall. In addition, the research results show that RANS over-predicts the corner separation [10], which will misestimate the effects of the control method on the corner flow. Therefore, the large-eddy simulation (LES) is adopted to obtain accurate predictions of the complex flow in a compressor cascade and to evaluate the aerodynamic performance of the cascade. The effect of the BBEW technique on corner stall is investigated and the underlying physical mechanisms are elucidated, with the aim of providing a reference for the application of this technique to control corner stall in compressor cascades.

**METHODOLOGY**

The example chosen for this study is a low-speed linear compressor cascade that has already been described in the literature [11]. Its thickness distribution is that of the NACA 65-009 blade. The geometry and detailed geometric parameters of the cascade are shown in Figure 1 and Table 1 respectively. More information about the cascade can be found in Reference 12. In addition, taking account of the laminar-turbulent transition makes the numerical simulation more complicated [13], but the transition on the suction surface can be eliminated provided that the upstream turbulence level is high [14]. In this context, the experiments performed by Ma [15] and Zambonini [16] and the numerical simulations by Gao [12] used tripping bands to trigger the turbulent transition and facilitate exploration of corner separation in a compressor cascade. To provide match with experimental results, the tripping bands are set on the suction and pressure surfaces, and their positions are the same as those in the experiments, as shown in Figure 2. The bands are 3.0mm wide and 0.3mm thick.

![Figure 1 Geometry of cascade [12].](image1.png)

<table>
<thead>
<tr>
<th>Table 1 Geometric parameters of cascade.</th>
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<tbody>
<tr>
<td>Symbol</td>
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<tr>
<td>--------</td>
</tr>
<tr>
<td>$c$</td>
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<tr>
<td>$\phi$</td>
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<td>$\gamma$</td>
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<tr>
<td>$s$</td>
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<td>$h$</td>
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<tr>
<td>$\beta_1$</td>
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<tr>
<td>$\beta_2$</td>
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</table>
A. Description of BBEW technique

The BBEW modeling code for designing the geometry of the BBEW cascade can be found in Ref. 17, and the BBEW modeling procedure is depicted in Figure 3. First, increase the number of profile sections near the endwall of the cascade. Second, The BBEW geometry of the last section at the endwall is recognized and generated according to the input BBEW parameters shown in Figure 4. The geometry of each section along the spanwise direction is composed of multi-Bézier curves in the BBEW region. \( ALM, AL1, AL2, AS1, AS2, AP1, AP2, \) and \( AP3 \) are the control parameters of the Bézier curves, which can change the shape of the curves. The parameters \( XLS, XLP, XS, \) and \( XP \) represent the corresponding chord-direction positions. All the above parameters are nondimensionalized using the chord length. The parameters \( YL, YLS, YLP, YS, \) and \( YP \) represent the outward extension distances of the BBEW contour in the normal direction based on the prototype. Third, the blade profile in a range from the root to a certain extent of the span is changed according to an elliptical or linear arrangement along the span. Finally, A curved surface is constructed connecting all of the new blade profile, and the BBEW cascade geometry is output.

![Figure 3 Process of BBEW modeling [17].](image)

A sensitivity analysis of the important parameters of the BBEW technique indicates that both the chord-direction position of the maximum BBEW width \( XS \) and the maximum BBEW width \( YS \) on the blade suction side have a significant effect on the aerodynamic performance of a BBEW cascade [17]. In addition, it should be noted that the aerodynamic performance of a compressor cascade can hardly be improved by the BBEW design on the pressure side. Therefore, this paper only adopts the BBEW technique on the suction side and focuses in the control effect of this technique on the corner stall in a compressor cascade. The chord-direction position of the maximum BBEW width \( XS \) is selected at \( 20%c_a \), and the maximum BBEW width \( YS \) is 17mm, expressed as \( (0.20,17) \). The geometry of the BBEW and prototype cascades are shown in Figure 5.

![Figure 4 Schematic definition of the BBEW parameters [17].](image)

![Figure 5 Geometry of the BBEW cascade and the prototype cascade: (a) geometry of the endwall profiles; (b) geometry of the cascades.](image)

B. Numerical Methods

1. Grid and Numerical setup

The commercial solver Ansys Fluent is used to conduct LES of corner stall control in the modified NACA65 cascade using the BBEW technique. The computational domain for the numerical simulations is a single blade passage with one pitch. The inlet lies \( 2.159c_a \) upstream of the leading edge, while the outlet lies \( 2.719c_a \) downstream of the trailing edge. The outlet sections 1 and 2 are the experimental measurement planes located at \( 0.363c_a \) and \( 0.907c_a \) downstream of the trailing edge, respectively. Owing to the symmetry of the cascade, only one half of the span has been simulated. For the computational grid an H-O-H type combined grid is adopted, consisting of \( 1.484\times10^7 \) grid points. To predict the flow
field structures accurately near the boundary layer and the corner stall, the grid near the wall is refined to ensure that $y^+$ is less than 1. Figure 6 shows the computational domain and mesh in the cascade.

**Figure 6 Computational domain and mesh.**

In this study, only an incidence angle of $4^\circ$ is investigated by LES. The freestream velocity is set at 40 m/s, yielding a chord-based Reynolds number $Re_c=3.82\times10^5$. The inlet boundary condition is set as a velocity inlet condition, and the velocity profile at the inlet is consistent with the experiments [15]. Because of the high computational cost of the inlet fluctuations [11], they are not considered in this paper. A uniform atmospheric static pressure is employed on the outlet plane. Both the blade surface and the endwall are assumed to be non-slip adiabatic walls. A symmetry condition is adopted at the midspan of the blade. Periodic conditions are adopted on the pitchwise boundaries of the calculation domain. For spatial discretization, a second order scheme, a bounded central differencing scheme, and a second order upwind scheme are used for the pressure term, the momentum term, and the energy term, respectively. A bounded second order implicit scheme with a fixed time step $5\times10^{-6}$ s is employed for temporal discretization, and the wall-adapting local eddy-viscosity model (WALE) is used to represent the subgrid-scale motions. In addition, a total of 17 periods are numerically simulated, and the time-averaged results are collected in the last 5 periods after the flow field has become periodic.

2. Validation of numerical methods

To assess the accuracy of the numerical methods, the LES results are validated by comparison with the experimental results. The total pressure loss coefficient is a key indicator for evaluating compressor performance and is given by

$$C_{pl} = \frac{P_{t,\infty} - P_t}{P_{t,\infty} - P_{s,\infty}}. \quad (1)$$

where $P_t$ is the total pressure, $P_s$ is the static pressure, and the subscript $\infty$ indicates the value at the inlet. The pitchwise-mass-averaged total pressure loss coefficient is given by

$$C_{pl}^* = \frac{\int_0^s C_{p1}(y,z) \rho(y,z) u(y,z) dy}{\int_0^s \rho(y,z) u(y,z) dy}. \quad (2)$$

where $u$ is the axial velocity, and $\rho$ is the density, which is taken to be constant, since the flow in this study is assumed to be incompressible. The spanwise distributions of total pressure loss coefficient at section 1 are plotted in Figure 7. The numerical and experimental results are clearly in good agreement, which proves that the numerical methods are correct and reliable. Therefore, the following study is carried out based on these numerical methods. It should be added that, except for the evolution of vortex structures, all the analysis in this paper is of the time-averaged results after the flow field has become periodic.

**Figure 7 Pitchwise-mass-averaged total pressure loss coefficient.**
RESULTS AND COMPARISONS

A. Overall performance

The total pressure loss is an important parameter to assess the effect of control measures. A comparison of the LES results for the mean total pressure loss coefficient at outlet section 1 between the prototype cascade and the BBEW cascade is depicted in Figure 8, together with the experimental results as a reference. The regions of wake and corner separation can be easily observed, as indicated by the larger value of mean $C_{p}$. Comparison of the numerical results for the prototype with the experimental results shows that the spanwise height of corner separation in the numerical simulation is slightly lower than that in the experiment, and the high-loss region with mean $C_{p} = 0.55$ is larger. The difference between the numerical and the experimental results may be due to the fact that only the velocity profile fitted based on the experimental data is considered in the inlet condition, but the inlet fluctuations are not taken into account. As a result, the momentum thickness of the endwall boundary layer in front of the leading edge of the cascade develops less, resulting in the larger corner separation losses and the smaller boundary layer losses. However, we focus on the control effect of the BBEW technique on corner stall in the compressor cascade, and the flow topology (Figure 11) and static pressure coefficient (Figure 14) of the prototype cascade predicted by the numerical methods are in good agreement with the experimental results. Therefore, the numerical deviation is acceptable. The LES results show that after the BBEW design of the prototype cascade, the spanwise height of corner separation reflected by mean total pressure loss coefficient is reduced from 0.15z/h to 0.13z/h. In addition, the high loss area with a mean $C_{p}$ of 0.55 is significantly decreased in both the spanwise and the pitchwise directions, indicating that the BBEW technique can weaken the corner stall.

![Figure 8 Contours of mean total pressure loss coefficient.](image)

A comparison of the pitchwise-mass-averaged total pressure loss coefficient at outlet section 1 between the prototype cascade and the BBEW cascade is presented in Figure 9. It can be observed that relative to the corner separation region of the prototype cascade, the $C_{p}$ of the BBEW cascade is slightly higher only in the range from 0.05z/h to 0.1z/h, and it is lower at other spanwise positions. To obtain an intuitive view of the effect of the BBEW technique on improving the total pressure loss, the method for analyzing the total pressure loss presented by Hergt [18] is adopted to decompose the loss into three parts: profile loss $C_{pl}$, corner separation loss $C_{csl}$, and boundary layer loss $C_{bl}$, as shown in Figure 9. This decomposition can be expressed as follows:

$$C_{p,global} = C_{pl} + C_{csl} + C_{bl}.$$  \hspace{1cm} (3)

where $C_{p,global}$ is the mass-averaged total pressure loss coefficient given by:

$$C_{p,global} = \frac{\int_{0}^{b/2} \int_{0}^{h/2} C_{p} \rho (y, z) u (y, z) dy dz}{\int_{0}^{b/2} \int_{0}^{h/2} \rho (y, z) u (y, z) dy dz}.$$  \hspace{1cm} (4)

$C_{pl}$ can be obtained near the midspan of the cascade and is generated by the friction of the flow around the blade profile. $C_{csl}$ is produced by corner separation and interaction between the corresponding vortices, and $C_{bl}$ is generated by the viscosity of the inlet flow acting on the endwall.
Compared with the prototype cascade, the relative changes in aerodynamic performance indices of the BBEW cascade are summarized in Table 2. At outlet section 1, the mass-averaged total pressure loss coefficient of the BBEW cascade is decreased by 2.44%, and accordingly, the profile losses, the corner separation losses, and the boundary layer losses are reduced by 2.74%, 1.35%, and 6.27%, respectively. Among them, due to the BBEW technique increases the dihedral angle, the boundary layer losses decrease most significantly. Unfortunately, the relative variations of the profile losses here are only of use for reference, because of some errors in the calculation of the symmetry boundary, which can be observed at the midspan in Figures 8 and 9.

The static pressure rise coefficient and the flow turning angle are also important in evaluating the aerodynamic performance of compressor cascades. The static pressure rise coefficient is:

$$C_{p,2} = \frac{P_{s,2} - P_{s,\infty}}{P_{s,\infty} - P_{s,\infty}}$$

where $P_{s,2}$ is the static pressure on the measurement plane and is computed in the downstream section 1. The flow turning angle is:

$$\Delta \beta = \beta_1 - \beta_2$$

where $\beta_1$ and $\beta_2$ are the actual inflow and outflow angles, which are obtained from the section 2. As shown in Table 2, both the static pressure rise coefficient and the flow turning angle of the BBEW cascade are improved compared with the prototype, but the variation range is small, which is only for reference.

**TABLE 2 Relative changes of the aerodynamic performance improvements for the BBEW cascade.**

<table>
<thead>
<tr>
<th>Performance factor</th>
<th>$\Delta C_{p,\text{global}}$</th>
<th>$\Delta C_{\text{pl}}$</th>
<th>$\Delta C_{\text{cas}}$</th>
<th>$\Delta C_{\text{bl}}$</th>
<th>$\Delta C_{\text{a}}$</th>
<th>$\Delta (\Delta \beta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative change</td>
<td>-2.44%</td>
<td>-2.74%</td>
<td>-1.35%</td>
<td>-6.27%</td>
<td>0.67%</td>
<td>0.89%</td>
</tr>
</tbody>
</table>

The aerodynamic blockage coefficient ($BL$) is an important parameter characterizing the throughput capability in the passage between cascades. It is given by:

$$BL = \frac{1}{h} \int_0^h \int_0^{1/2} \left( \rho_s V_s - \rho V \right) dy dz$$

where $V$ is the velocity, the subscript $m$ represents the variables in the main flow region outside the boundary layer, and $m$ is the inlet mass flow rate.

Figure 10 shows the axial distribution of the aerodynamic blockage coefficient. In the Figure 10, from the leading edge to 39.2% of the axial chord, the aerodynamic blockage coefficient of the BBEW cascade is smaller than that of the prototype, and presents a trend of decreasing first and then increasing. At 0.072x/c, the aerodynamic blockage coefficient decreases by 10.32% compared with the prototype, reaching the maximum reduction. As mentioned above, the maximum BBEW width is located at 20% of the axial chord, the BBEW direction is normal to the suction surface. Therefore, the axial position of the minimum aerodynamic blockage coefficient is closely related to the position of the maximum BBEW width. From 0.712x/c to the trailing edge, the $BL$ of the BBEW cascade is smaller than the prototype, and the closer to trailing edge, the greater the decrease of aerodynamic blockage coefficient. At 96.8% of the axial direction, the $BL$ decreases by 4.81%. The main reason for the decrease of aerodynamic blockage near the trailing edge is that the BBEW method is beneficial to the corner stall.
In conclusion, the above comparisons of the aerodynamic parameters indicate that the BBEW technique can improve the aerodynamic performance of a compressor cascade to a certain extent.

B. Near-wall flow

The topology of the corner stall and the contours of the static pressure coefficient on the hub and the blade surface are presented in Figure 11, which shows many important characteristics of the corner flow, including the red separation lines, the blue attachment lines, and some critical points, such as the saddle point S, the node N, and the focus F. These critical points indicate that the LES results obey the index rule [19].

As shown in Figure 11(a) and (b), the flow topology of the prototype cascade calculated by the LES method is in good agreement with the experimental results. As can be seen from Figure 11(b), in the flow field of the prototype cascade, the saddle point S2 formed by part of the suction branch of the corner vortex [CV(S)] rising from the endwall to the suction side [20] represents the onset of corner stall, which is located at 53.5% of the axial chord. The spanwise separation height of the large reverse-flow region containing the critical points F3 and S3 on the suction surface reaches 0.175z/h. The separation line I separated from the saddle point S2 and the separation line II from the adjacent blade meet in the passage to form a large separation vortex F2 on the hub characterizing the hub-corner stall [1] in a compressor cascade, which rolls up the endwall boundary layer of the whole inlet flow. Due to the existence of transverse pressure gradient, the separation vortex accumulates toward the corner region formed by the trailing edge of the suction surface and the endwall, and, at the same time, coils the corner reverse flow. The interaction of the separation vortices F2 and F3 results in the corner stall.

However, in the (0.20,17) cascade flow field, the suction branch of the corner vortex rises from the endwall along the suction side and does not form a saddle point at the junction between the suction surface and the hub. With the increasing number of critical points on the suction surface, the vortex structures become more complex, but the intensity of the vortices significantly decreases, which clearly reveals a reduction in the extent of the reverse-flow region, and the spanwise height of the corner separation decreases to 0.127z/h. The inlet boundary forms a saddle point S2 in the middle of the passage, which represents the onset of corner stall. It is located at 46.26% of the axial chord, which is earlier than
the initial position of corner stall in the prototype. The red streamline 1 passing through the saddle point S2 divides the inlet flow into two parts. The inlet boundary layers between the separation streamlines I and II, I and III leave the endwall at F2 and F4, respectively, forming a small separation vortex. Compared with the single large characteristic vortex on the endwall of the prototype, the strengths of the two small separation vortices decrease, and the pitchwise range of the corner separation also decreases.

The contour of the skin friction coefficient on the suction side is plotted in Figure 12 in which the regions of the low skin friction coefficient inside the three-dimensional corner separation and near its spanwise peak correspond to the cores of the corner stall and the concentrated shedding vortex (CSV) respectively.

![Figure 12 Contours of skin friction coefficient on the blade suction side](image)

**Figure 12** Contours of skin friction coefficient on the blade suction side

It is obvious that the spanwise positions of the cores of the concentrated shedding vortex and the three-dimensional corner separation in the BBEW cascade are significantly lower than those in the prototype. The core of three-dimensional corner separation in the BBEW cascade is concentrated below 5% of the span, and the extent of the region of low skin friction coefficient is reduced, which indicates that the strengths of the separation vortices are decreased. Compared with the prototype, there is a larger area of high skin friction coefficient near the leading edge of the spanwise root in the BBEW cascade, as shown in the blue dashed box, which indicates that the corner vortex and other low-energy fluid flows in this area are improved and the energy is enhanced. In addition, the range of high skin friction coefficient shown by the yellow dashed box for the BBEW cascade is larger than that of the prototype cascade, and so it can be deduced that the energy of the fluid at this position is increased, which is beneficial in restraining the spanwise development of three-dimensional corner stall and thereby effectively reducing the spanwise height of corner separation.

In conclusion, although the flow structures of the corner stall become more complex in the BBEW cascade flow field, the spanwise and pitchwise ranges of corner separation are reduced. The strengths of the main separation vortices on the suction side and the endwall decrease, indicating that the corner flow is improved.

C. Three-Dimensional Flow Topology

To obtain a deeper understanding of the three-dimensional flow topology of the prototype and the BBEW cascade, the three-dimensional flow structures at the main critical points in this region are represented in Figure 13 by the rods colored according to the mean spanwise velocity. These rods are equivalent to the volume streamlines, which can reveal the strength of twist, while the spanwise velocity indicates the direction of fluid transport.

![Figure 13 Velocity rods in the corner stall region.](image)

**Figure 13** Velocity rods in the corner stall region.

For the prototype cascade, it is clear from the rod near the focus F3 on the suction surface that the vortex carries part of the suction branch of the corner vortex and the fluid from the adjacent blade up along the suction surface and moves downstream to form a concentrated shedding vortex. The vortex F5 transports partial fluid from the pressure branch of the corner vortex and the adjacent blade toward the endwall. By contrast, the separation vortex F2, which indicates the existence of hub-corner stall, transports the whole inlet boundary layer and the fluid near the vortex F5 away from the endwall, finally carrying them downstream of the cascade.
For the BBEW cascade, the fluid from the inlet lifts off the wall in the vortices F2, F4 and F5 and then moves downstream. By combining the limiting streamlines and rods, it can be observed that the vortices N6, F7 draw fluid from the pressure branch of the corner vortex and a fraction of the fluid from the adjacent blade to the suction surface and the hub, respectively, and then interact with the vortices F2 or F4, finally developing together with them.

Compared with the prototype cascade, both the twist (or vorticity) and the rise height from the endwall of the marked vortices in the BBEW cascade are greatly decreased, indicating that the losses in the corner region are reduced and the flow is clearly improved.

**MECHANISM ANALYSIS**

The above analysis shows that after the BBEW design, the flow in the corner region is reorganized so that the topological structure changes. The physical mechanism of the BBEW technique to improve the corner stall flow is analyzed from the following aspects.

**A. Distribution of The Static Pressure**

From the contour of the static pressure coefficient in Figure 11(c), it can be observed that there is an obvious low-pressure area (shown by the red dotted box) at the position of the maximum BBEW width. To further understand fluid field information, the static pressure coefficient around the prototype and the BBEW cascades at 1.4% and 5.4% of the span are plotted in Figure 14. At 1.4% of the span, the original inverse pressure gradient on the suction surface is transformed into a strong local positive pressure gradient in the range of 2.4% - 5.3% axial chord in the BBEW cascade. At 5.4% of the span, i.e., slightly higher than the spanwise highest position of the BBEW geometrical modification surface, the BBEW cascade also forms a local positive pressure gradient in the range of 3.4% - 10% axial chord, but the strength is relatively weak. The region of the local positive pressure gradient mentioned above is located near the axial position of the maximum BBEW width. The axial force generated by the strong local positive pressure gradient can accelerate the nearby flow and increase its momentum. In Figure 12(b), the mean friction coefficients in the regions within the yellow and blue dashed boxes for the BBEW cascade are larger than those of the prototype, which confirms the effect of this technique in accelerating the fluid.

In addition, the spanwise distribution of the static pressure coefficient for the prototype and the BBEW cascade at chord-direction position of the maximum BBEW width are depicted in Figure 15. When it is below 2.8% of the span, the static pressure coefficient of the BBEW cascade decreases sharply from the root along the span. The spanwise force generated by the strong spanwise pressure gradient can transport the low-momentum fluid from high pressure to low pressure and thereby avoid accumulation of low-energy fluid on the endwall.

Therefore, the axial and spanwise forces generated near the position of the maximum BBEW width are among the reasons why the corner stall is reduced.

![Figure 14 Static pressure coefficient at different spanwise positions.](image)

![Figure 15 spanwise distribution of the static pressure coefficient at chord-direction position of the maximum BBEW width.](image)
B. Development of Boundary Layer in the Corner Region

To further explore the influence of the BBEW technique based on increasing dihedral angle on the intersection of boundary layers in the corner, the contours of the mean axial velocity at different positions of the axial chord as shown in Figure 16. Obviously, the thicknesses of the boundary layer in the corner of the BBEW cascade are lower than those of the prototype cascade at 20% and 52% axial chord. At 84% of the axial chord, compared with the prototype, the range of the minimum mean axial velocity of the BBEW cascade is clearly reduced. Also, low-energy fluid no longer accumulates in the corner, but leaves the suction side and moves pitchwise, which is consistent with the corner stall topology mentioned above.

It can be inferred that the BBEW technique can effectively weaken the intersection of boundary layers in the corner by increasing the dihedral angle.

C. Evolution of Vortex Structures

Figures 17 and 18 show the evolution of turbulent coherent structures in the passages of the prototype and the BBEW cascade within one period, as represented by isosurfaces of the Q criterion colored according to the velocity magnitude. The main vortices are marked on the figures. For both the prototype and the BBEW cascade, there are separation vortices induced mainly by the leading-edge corner vortex or the leading-edge horseshoe vortex, such as SV6 in Figure 17(a). Affected by the corner stall, the separation vortices rise along the suction surface at the starting position of the three-dimensional corner stall, and develop downstream to form passage vortices, such as SV1, ..., SV5 in Figure 17(a), until they are broken. The whole process continues to repeat itself. By comparing the turbulent coherent structures of the BBEW cascade with the prototype cascade, it is not difficult to see that the spanwise height of the concentrated shedding vortex decreases and the region of three-dimensional corner separation shrinks. These results are consistent with the conclusions from the analysis of flow topology. Note that the areas enclosed by the black dashed line in Figure 18, from the leading edge to about 70% of the axial chord, in which the vortex structures on the geometric modification surface of the BBEW are significantly restrained. This occurs because the increase in dihedral angle weakens the intersection of boundary layers, the axial force accelerates the surrounding fluid, and the spanwise force carries the low-energy fluid upward, reducing accumulation on the endwall. In addition, the suction branch of the corner vortex is effectively controlled in the BBEW cascade, which is the main reason why the saddle point indicating the onset of corner stall is not generated by the suction branch of the corner vortex in the corner flow topology.

\[ t = \frac{\pi}{3} \]
\[ t = 2\frac{\pi}{3} \]
\[ t = \pi \]

Figure 17 Evolution process of the turbulent coherent structures in the passage of the prototype cascade within one period \((Q = 42V_{\infty}^2/c^2 = 3 \times 10^6)\).
In summary, the physics mechanisms of the BBEW technique to control the corner stall are as follows: (1) At the chord-direction position of the maximum BBEW width, the BBEW method generates both an axial force and a spanwise force. The former accelerates the nearby fluid, and the latter transports low-energy fluid upward to reduce accumulation on the endwall. (2) The increased dihedral angle weakens the intersection of boundary layers, and also inhibits the development of the corner vortex.

CONCLUSIONS

The influence of the blended blade and endwall (BBEW) technique on corner stall in a modified NACA65 compressor cascade with a chord-based Reynolds number of \( Re_c = 3.82 \times 10^5 \) has been investigated. The BBEW cascade has been compared with the prototype cascade, and the effects of this technique have been thoroughly analyzed from the perspectives of aerodynamic performance, flow topology and physical mechanisms. The following three important conclusions can be drawn from this study:

(1) The total pressure loss of the BBEW cascade is reduced by 2.44% relative to the prototype cascade. The aerodynamic blockage near the leading and trailing edge decreases markedly, which means that the throughflow capacity is enhanced. All the aerodynamic parameters show that the BBEW technique can improve the aerodynamic performance of compressor cascades under corner stall conditions to a certain extent.

(2) The corner stall topology can be changed by the BBEW technique, in which a single large separation vortex on the endwall of the prototype cascade is weakened and broken into two small separation vortices. Both the twist and the rise height from the endwall of the main vortices are greatly decreased, indicating that the intensity of corner stall is decreased, and so the region of three-dimensional corner separation is diminished.

(3) the BBEW technique improves the aerodynamic performance of the compressor cascade under corner stall conditions through the following mechanisms: (a) The BBEW technique generates both an axial force and a spanwise force near the chord-direction position of the maximum BBEW width. The axial force accelerates the surrounding fluid and increases the kinetic energy, while the spanwise force transports the low-energy fluid upward to reduce accumulation on the endwall. (b) The increase in dihedral angle weakens the intersection of boundary layers and inhibits the development of the corner vortex, which is also the main reason for the significant reduction of the boundary layer losses by 6.27%.

NOMENCLATURE

- \( c \): Chord
- \( \varphi \): Camber angle
- \( \gamma \): Stagger angle
- \( s \): Pitch
- \( h \): Blade span
- \( \beta_1' \): Design inflow angle
- \( \beta_2' \): Design outflow angle
- \( \beta_i \): Actual inflow angle
- \( \beta_o \): Actual outflow angle
- \( \Delta \beta \): Flow turning angle
- \( C_{pt} \): Total pressure loss coefficient
- \( P_t \): Total pressure
- \( P_s \): Static pressure
- \( \rho \): Density
- \( u \): Instantaneous velocity in x direction
\( x, y, z \) Cartesian coordinates of the cascade
\( Cp \) profile losses
\( C_{col} \) corner separation losses
\( C_{bll} \) boundary layer losses
\( C_{p2} \) Static pressure rise coefficient
\( BL \) Aerodynamic blockage coefficient
\( V \) Velocity
\( \dot{m} \) Inlet mass flow rate
\( t \) Time
\( T \) Period
\( Q \) Q criterion

**Subscripts**

\( \infty \) Parameters of inlet
\( m \) Variables in main flow

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