Investigation of the Effect of Relative Circumferential Position on a Tandem Conformal Diffuser in a Mixed-Flow Compressor

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Abstract. Tandem diffusers are widely employed to broaden the operating range and mitigate aerodynamic losses in compressors. However, they often suffer from significant accumulation of low-momentum fluid near the end walls, resulting in flow non-uniformity at the diffuser outlet. To address this issue, this study proposes a scheme to vary the relative circumferential positions of the fore and aft blades to optimize the aerodynamic performance of the compressor. Computational results indicate that the compressor achieves its peak stage efficiency at a circumferential position of 25%, where the total pressure loss coefficient is reduced by 4.4%. This configuration minimizes the accumulation of the boundary layer on the suction surface to the greatest extent, thereby delaying or suppressing flow separation on the aft blade. Consequently, this reduces losses and enhances the diffusion capability of the tandem conformal diffuser as well as the overall performance of the mixed-flow compressor.

Keywords: Tandem diffusers; Mixed-Flow Compressor;Tandem cascade ;Numerical simulation.

1. Introduction

Experimental and theoretical research on tandem cascades began abroad as early as the 1950s and 1960s. In 1974, NASA initiated studies on tandem cascades while investigating high-loading axial flow compressors [1]. Domestically, Wu Guochuan [2], Miao Houwu [3], and others conducted systematic theoretical and experimental investigations on tandem cascades, revealing that tandem blades possess advantages such as lower losses and a wider operating range compared to single rows of blades. In recent years, numerical simulations by Li Shaobin [4], Liu Lei [5], Yang Yong [6], and others have demonstrated that selecting a reasonable relative circumferential position can mitigate flow separation on the aft blade, resulting in a more uniform velocity distribution at the diffuser outlet.

While extensive research exists regarding tandem blades in axial and centrifugal compressors, their application in mixed-flow compressors remains relatively unexplored and warrants further in-depth investigation. In this paper, four configurations of tandem conformal diffusers with distinct relative circumferential positions were obtained by varying the positions of the fore and aft blades. Numerical simulations were conducted on the flow fields of these four tandem conformal diffusers under identical boundary conditions to investigate and analyze the influence of different circumferential tandem positions on the performance of the diffuser.

2. Numerical Simulation Model and Validation

2.1 Description of Validation Model and Mesh Generation

This section focuses on the high-efficiency compact mixed-flow compressor designed by Nanjing University of Aeronautics and Astronautics. The compressor comprises a mixed-flow impeller and a tandem conformal diffuser with splitter blades.

The three-dimensional model of the mixed-flow compressor was generated using the BladeGen module of ANSYS software, and the mesh was generated using the AutoGrid5 module of NUMECA software. An O4H-type topology was employed. The Spalart-Allmaras (S-A) model was adopted as the turbulence model. To meet the requirement of $y+<10$ for the S-A model, the mesh was refined in the near-wall regions and at the leading and trailing edges of the blades, with the height of the first grid layer near the wall set to 0.003 mm. To ensure the mesh quality satisfied the requirements for subsequent numerical calculations, the minimum orthogonality angle was maintained above 15°, the maximum aspect ratio below 260, and the maximum expansion ratio of adjacent cells below 5. A single blade passage was selected as the computational domain. A schematic of the generated partial mesh is shown in Fig. 1.

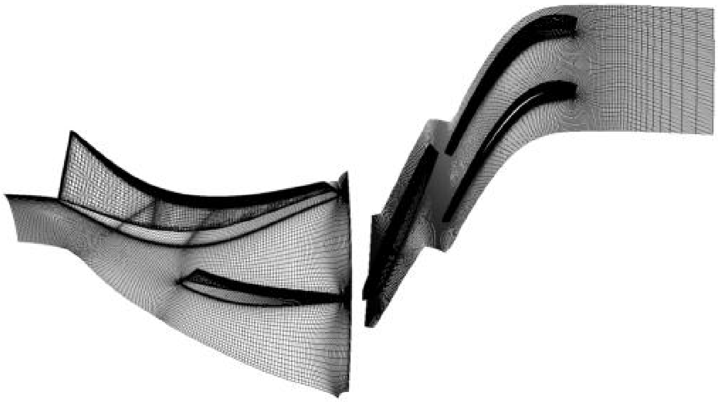

Fig. 1 Schematic of the grid for the mixed-flow compressor

2.2 Grid Independence Study

Three grids with varying densities(2.6×106、3.2×106and3.8×106grid points）were selected to conduct the grid independence verification. As illustrated in Fig. 2, the overall trends of the compressor characteristic curves under different grid sizes are consistent. It can be observed that with 2.6×106 grid points, the pressure ratio and performance of the mixed-flow compressor are higher than the calculated values obtained with the denser grids. However, the performance curves at 3.2×106 grid points show good agreement with those at 3.8×106 grid points. This indicates that the gain in computational accuracy achieved by further increasing the grid number is no longer significant, and the overall performance parameters of the mixed-flow compressor remain basically unchanged. Consequently, the grid size of 3.2×106 satisfies the requirements for grid independence.

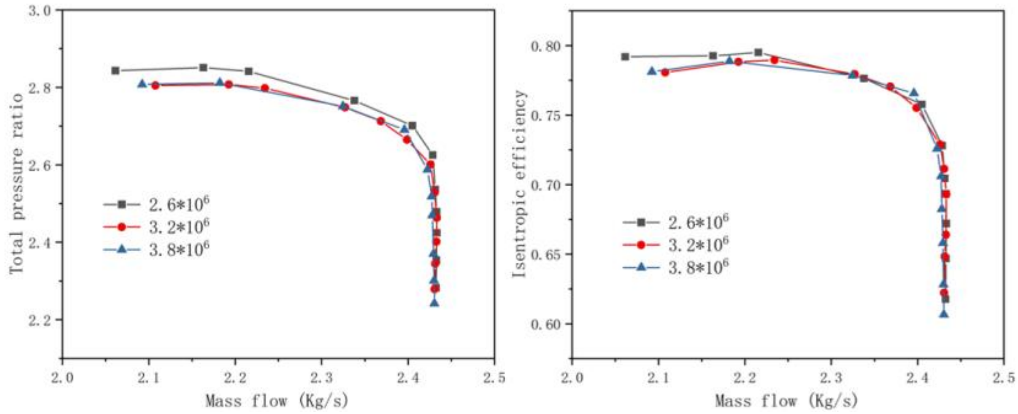

Fig. 2 Grid independence verification

3. Definition of Relative Circumferential Tandem Position

This chapter takes the previously mentioned tandem conformal diffuser as the baseline and conducts optimization based on this configuration. To ensure the consistency of other design parameters, only the relative circumferential position of the fore-blade was varied during the adjustment process, while all other geometric parameters remained unchanged.

In this paper, the parameter RCP=a/b is used to define the relative circumferential tandem position between the fore and aft blades of the tandem conformal diffuser. In this formula,a represents the circumferential distance between the trailing edge of the fore-blade and the leading edge of the aft blade,and b denotes the pitch of the aft blade. A splitter blade is added between two main blades, positioned centrally within the passage. The splitter blade is duplicated from the main blade and possesses identical geometric parameters.Figure 3(a) presents the schematic diagram defining the circumferential tandem position of the tandem

When adjusting the circumferential tandem position, the position of the aft blade was held constant, while the fore-blade was translated circumferentially to the designated locations. For this investigation, four relative circumferential positions (RCP=0%、25%、50% and 75%) were selected. Consequently, a total of four configurations were established for numerical simulation to compare and analyze the influence of these models on the performance of the compressor components. The three-dimensional computational models of the tandem conformal diffuser at different circumferential tandem positions are shown in Fig. 3(b).

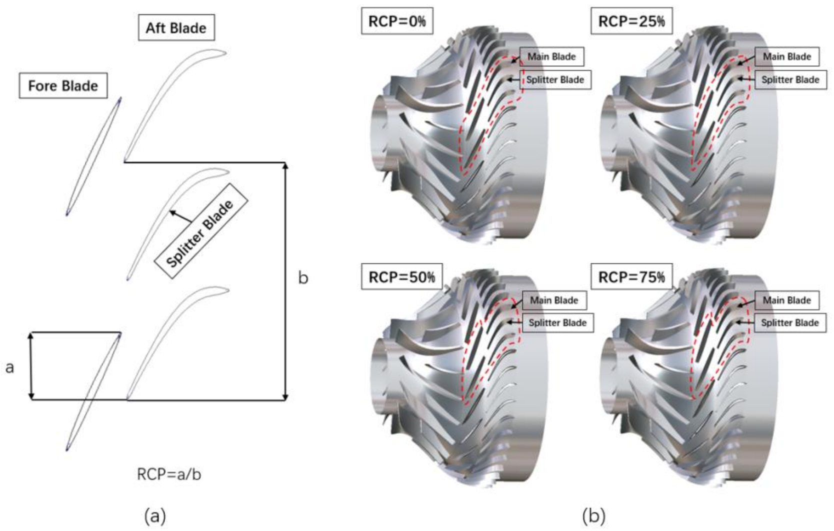

Fig. 3 Schematic of the relative circumferential tandem position

4. Analysis of Results

4.1 Characteristic Curves and Comparison of Overall Performance

Numerical simulations were conducted for the four positioning schemes described above. Consequently, the performance curves, specifically the total pressure ratio versus mass flow rate and isentropic efficiency versus mass flow rate, were obtained for the tandem conformal diffuser at different circumferential positions.

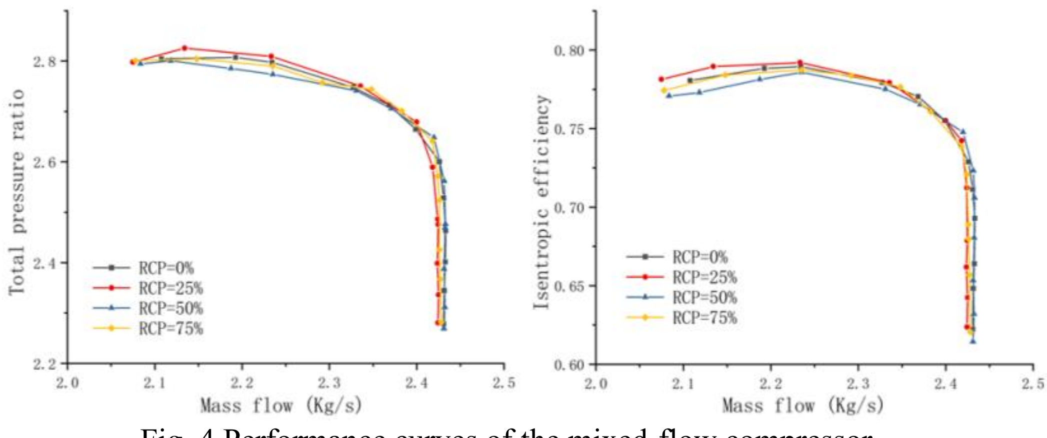

Fig. 4 Performance curves of the mixed-flow compressor

As illustrated in Fig. 4, distinct differences are observed in the performance curves of the mixed-flow compressor at various circumferential positions. First, a variation in the surge point is observable. The surge mass flow rate for the 0% position is approximately 2.11 kg/s, whereas for the other three positioning schemes, it is around 2.07 kg/s. This indicates that the operating range of the compressor has been extended to a certain extent.As the mass flow rate further decreases, it is evident that the total pressure ratio at the 25% position shows an improvement compared to the 0% baseline. The pressure ratio is lowest at the 50% position, while at the 75% position, it is slightly lower than that of the 0% case. Overall, as the circumferential position varies from 25% to 75%, the total pressure ratio undergoes a process of initial decrease followed by an increase.Observing the mass flow-efficiency characteristic curve , at the design point (2.23 kg/s), the isentropic efficiency is highest at the 25% position, peaking at 78.7%, whereas it is lowest at the 50% position. Broadly speaking, as the circumferential position shifts from 25% to 75%, the efficiency curve similarly exhibits a trend of decreasing first and then increasing.The rise in efficiency at the 75% position is hypothesized to stem from reasons similar to those at the 25% position. At both positions, the fore-blade forms a specific gap channel with the aft blade. The distinction lies in the fact that at the 25% position, the pressure surface of the fore-blade is adjacent to the suction surface of the aft blade, whereas at the 75% position, the pressure surface of the fore-blade is proximate to the pressure surface of the aft blade.

Figure 5 illustrates the comparison of the total pressure loss coefficients for the tandem conformal diffuser at different relative circumferential positions under the design mass flow rate.As observed from the figure, under identical inlet conditions, the total pressure loss coefficients for the four distinct circumferential positions vary. Specifically, the tandem conformal diffuser with an RCP of 25% exhibits a total pressure loss coefficient of approximately 0.355, representing a reduction of about 4.4% compared to the baseline scheme (RCP = 0%).Overall, the configuration with an RCP of 25% yields a lower total pressure loss coefficient compared to the other three schemes, indicating superior aerodynamic performance of the tandem conformal diffuser and higher efficiency of the tandem compressor.

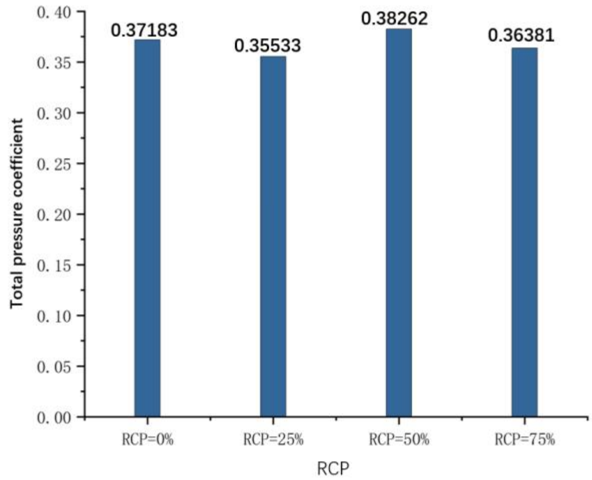

FIG. 5. Comparison of total pressure loss coefficients for the mixed-flow compressor

4.2 Analysis of Meridional Flow in the Tandem Conformal Diffuser

Figure 6(a) presents the contours of the absolute Mach number and streamlines on the meridional plane of the tandem conformal diffuser at different circumferential positions.At the 25% position, it is observed that the extent of the high-speed region near the shroud of the aft blade is larger than that at the 0% position. Conversely, at the 50% position, the high-speed region near the shroud of the aft blade shows a noticeable reduction compared to the 0% position. Furthermore, at the 75% position, this high-speed region exhibits a slight increase compared to the 50% position.In addition, compared to the 0% baseline, although the area of the low-speed region near the hub of the aft blade remains relatively unchanged for the remaining three schemes, the Mach number decreases slightly in all cases.

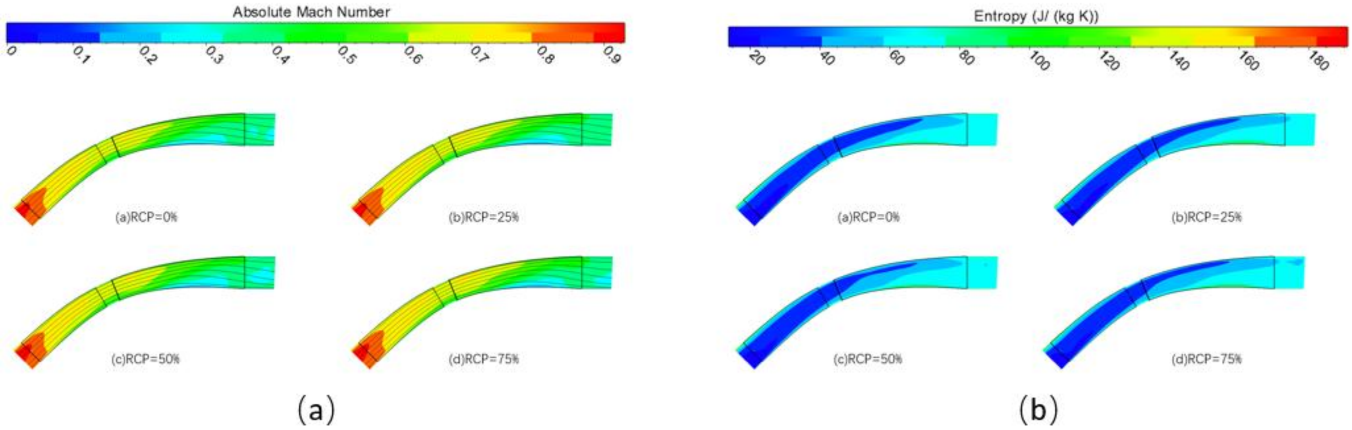

FIG. 6. Contours of absolute Mach number and entropy on the meridional plane at different circumferential positions

Figure 6(b) presents the contours of entropy distribution on the meridional plane of the tandem conformal diffuser at different circumferential positions. It is evident from the figure that the primary differences are concentrated near the shroud of the aft blade.At the 50% position, the extent of the low-entropy region is the smallest compared to the other three schemes. Consequently, this configuration yields the highest entropy generation, resulting in the maximum energy loss and the lowest efficiency.Conversely, at the 25% position, it is observed that the overall extent of the low-entropy region is the largest, and the entropy value is the lowest. Therefore, the overall entropy generation is smaller than that of the other three circumferential positions, leading to the minimum energy loss and the highest efficiency.

4.3 Analysis of the Internal Flow Field of the Tandem Conformal Diffuser

Figure 7 presents the contours of Mach number and streamlines at a 10% span of the tandem conformal diffuser, as well as the distribution of the static pressure coefficient(Cp)on the aft blades (including main and splitter blades), under four different relative circumferential positions of the fore-blade.At the 0% circumferential position, distinct low-speed regions are observed near the trailing edges of the suction surfaces of both the main and splitter blades in the second row. When the circumferential position shifts to 25%, the location of boundary layer separation on the suction side of the splitter blade changes, occurring noticeably later than at the 0% position. This is corroborated by the static pressure coefficient distribution, where a distinct decrease in Cp on the suction side of the splitter blade is observed compared to the 0% baseline.This phenomenon occurs because, as the fore-blade moves circumferentially, high-energy fluid from the suction surface of the fore-blade injects new momentum into the suction surface of the splitter blade. This reduces the accumulation of boundary layer thickness and delays flow separation on the splitter blade's suction surface. Conversely, due to the absence of this high-energy fluid acting on the main blade's suction surface at this position, an increase in the static pressure coefficient is observed near X/L=0.25.This indicates a rise in local static pressure and a corresponding decrease in velocity on the blade surface. Simultaneously, a tendency for boundary layer separation to advance toward the leading edge is observed at the trailing edge of the suction surface, accompanied by an increased extent of the boundary layer.Similarly, at the 75% circumferential position, a rearward shift of the separation point (delayed separation) on the main blade is observed, along with intensified boundary layer separation on the splitter blade. It is evident that this suppression of boundary layer separation is closely related to the relative circumferential position; the high-energy fluid from the suction surface of the fore-blade can effectively inhibit boundary layer separation on the suction side of the adjacent aft blade.

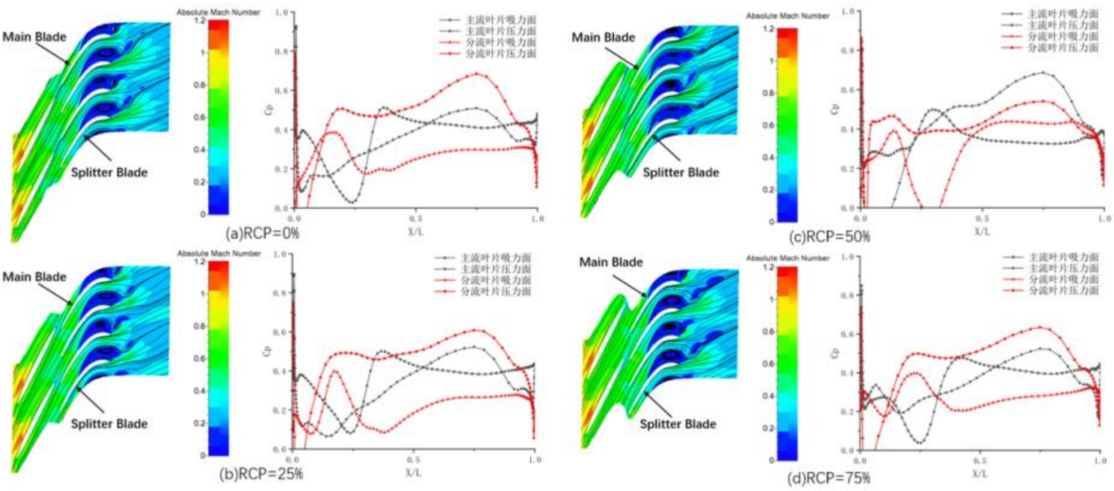

FIG. 7. Distributions of Mach number, streamlines, and static pressure coefficient at a 10% span under different circumferential positions

Figure 8 illustrates the distributions of entropy at a 10% span of the tandem conformal diffuser under four different relative circumferential positions of the fore-blade.At the 0% circumferential position, distinct high-entropy regions are visible near the trailing edges of the suction surfaces of both the main and splitter blades in the second row. Notably, the extent of the high-entropy region at the trailing edge of the splitter blade is larger than that of the main blade, indicating a greater energy loss at the trailing edge of the splitter blade.At the 25% circumferential position, as high-energy fluid from the suction surface of the fore-blade injects new momentum into the suction surface of the splitter blade, a significant reduction in the extent of the high-entropy region at the trailing edge of the splitter blade is observed. Although the high-entropy region at the trailing edge of the main blade expands slightly, the overall level of entropy generation is lower than that in the 0% case.When the circumferential position is further increased to 50%, the aerodynamic interaction between the fore-blade and the aft blade diminishes. Consequently, the high-entropy region near the trailing edge of the splitter blade re-expands, leading to a corresponding increase in overall energy loss.At the 75% circumferential position, the high-energy fluid from the suction surface of the fore-blade injects new momentum into the suction surface of the main blade, resulting in a scenario similar to that observed at the 25% position (but on the main blade). Overall, the 25% circumferential position yields the minimum overall energy loss for the diffuser, with the lowest entropy values compared to the other cases.

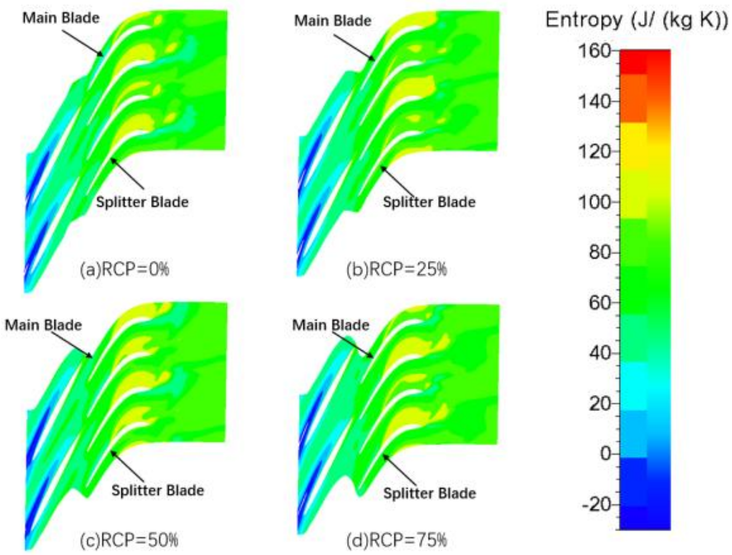

FIG. 8. Distributions of entropy at a 10% span under different circumferential positions

Figure 9 presents the distributions of limiting streamlines and entropy on the suction surfaces of the tandem conformal diffuser at four different circumferential positions, serving to illustrate the influence of these positions on the flow field structure of the suction side.To facilitate the observation of the impact of different circumferential positions on boundary layer separation: the upper part of the figure displays the limiting streamlines and entropy distributions on the suction surface of the splitter blade, while the lower part shows those for the main blade.Regarding the splitter blade, compared with other circumferential positions, it is observed that at the 25% position, the point of boundary layer separation on the suction surface exhibits a more distinct trend of rearward shift (delayed separation). Furthermore, the entropy generation associated with boundary layer separation on the blade surface is attenuated.In addition, for the main blade at the 25% position, a noticeable trend of delayed boundary layer separation is also observed. Compared with the other three positioning schemes, the high-entropy region in the fore-to-mid section of the main blade's suction surface is significantly reduced.This suggests that when the tandem conformal diffuser is at this circumferential position, the losses induced by boundary layer separation are relatively small, which is conducive to the efficient organization of flow within the diffuser.

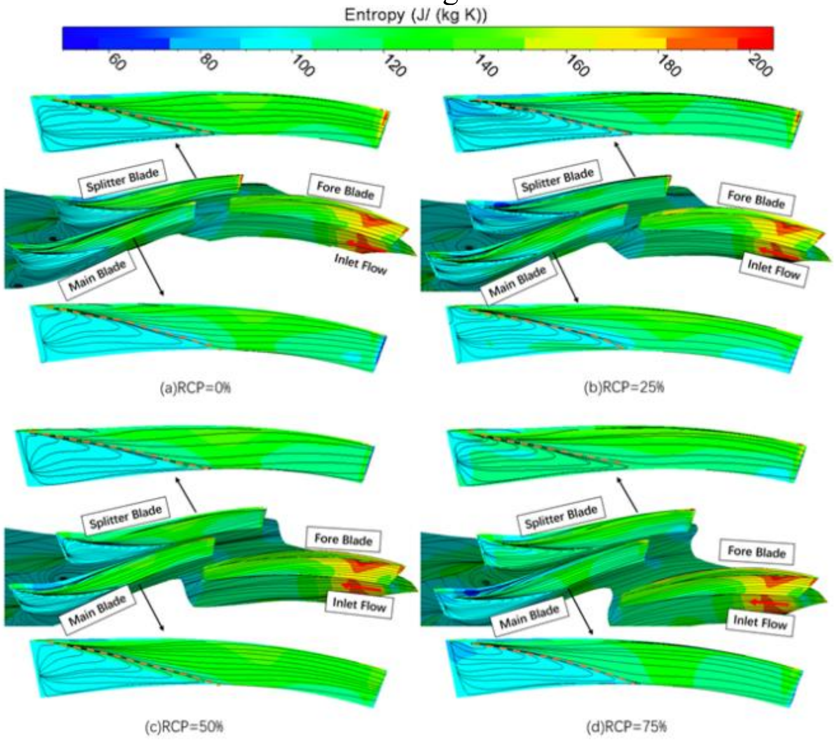

FIG. 9. Distributions of limiting streamlines and entropy on the suction surface of the tandem conformal diffuser at different circumferential positions

5. Summary

In this chapter, numerical simulations were employed to investigate the influence of the tandem conformal diffuser, with its fore-blade at various circumferential positions, on the stage aerodynamic performance of the mixed-flow compressor. The following conclusions can be drawn:

1.Significant differences are observed in the stage aerodynamic performance of the mixed-flow compressor equipped with the tandem conformal diffuser at different relative circumferential positions. At the design point, the stage efficiency of the compressor is optimal at a circumferential position of 25%, reaching a peak efficiency of 78.7%. Overall, as the circumferential position varies from 25% to 75%, the efficiency curve undergoes a process of initial decrease followed by an increase.

2.Under identical inlet conditions, the total pressure loss coefficients for the four distinct circumferential positions are not consistent. Specifically, the tandem conformal diffuser with an RCP of 25% exhibits a coefficient of total pressure loss of approximately 0.355, representing a reduction of about 4.4% compared to the baseline scheme (RCP = 0%). Overall, the configuration with an RCP of 25% yields a lower total pressure loss coefficient compared to the other three schemes, indicating superior aerodynamic performance of the tandem conformal diffuser and higher efficiency of the tandem compressor.

3.An analysis was conducted on the flow fields under the design mass flow rate for the four different circumferential positions. The results indicate that the variation in the circumferential position of the fore-blade essentially results in a redistribution of the outlet flow field of the fore-blade. This alters the location where the high-momentum flow from the fore-blade interacts with the aft blade, thereby influencing the development of the boundary layer on the second row of blades and ultimately modifying the internal flow field of the tandem conformal diffuser. Overall, at the 25% position, the high-momentum fluid from the fore-blade is able to inject momentum into the second row of blades to the greatest extent. This reduces the accumulation of the thickness of the boundary layer on the suction surface , delays or suppresses flow separation on the aft blade, and reduces losses. Consequently, this enhances the diffusion capability of the tandem conformal diffuser and the overall performance of the mixed-flow compressor. Furthermore, the extent of the low-speed region at the outlet section is minimized at the 25% position, indicating the best flow conditions at the outlet. These findings suggest that, among the four arrangements considered in this study, the circumferential position of 25% is the optimal solution.

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