Postprint: Study on Unsteady Flow in Tandem Cascade Diffusers

Authors: Zhou Li, Li Yan, Wang Zhanxue

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Abstract

Numerical simulation methods were employed to investigate the unsteady flow in a tandem blade cascade diffuser. The results indicate that the internal flow within a centrifugal compressor equipped with a tandem blade cascade diffuser is characterized by a strongly unsteady three-dimensional viscous main flow and clearance flow as its primary features. The flow inside the tandem blade cascade diffuser exhibits significant unsteadiness, with the propagation of pressure fluctuations attenuating rapidly within the front blade row passage. The dominant frequency of pressure fluctuations in the front blade row passage of the diffuser is the impeller blade passing frequency. Near the leading edge of the rear blade row, the dominant frequency of pressure fluctuations becomes 0.5 times the blade passing frequency. Pressure fluctuations at the inlet of the tandem blade cascade diffuser are primarily excited by the impeller; at the tandem cascade gap, the impeller wake transported by the main flow interacts and superimposes with the clearance flow and front blade row wake, constituting a new excitation source for pressure fluctuations at the rear blade row leading edge. Compared to regions near the hub and tip, pressure fluctuations at the mid-span of the front blade row leading edge are subjected to more intense excitation from the impeller main flow and splitter blade wake.

Full Text

Preamble

Numerical Investigation of Unsteady Flow in Tandem Cascade Diffuser

ZHOU Li, LI Yan, WANG Zhan-Xue
(School of Power and Energy, Northwestern Polytechnical University, Xi’ an 710072, China)

Abstract: Numerical simulation was employed to investigate the unsteady flow field in a tandem cascade diffuser. Results show that the internal flow of a centrifugal compressor with a tandem cascade diffuser is characterized by a strongly unsteady, three-dimensional viscous main flow and gap flow. The flow within the tandem cascade diffuser exhibits significant unsteadiness, and the propagation of pressure fluctuations attenuates rapidly within the front cascade passage. The dominant frequency of pressure fluctuation in the front cascade of the diffuser is the blade passing frequency (BPF) of the impeller, while it shifts to 0.5 times the BPF near the leading edge of the rear cascade. The pressure fluctuation at the diffuser inlet is primarily excited by the impeller. In the gap between the tandem cascades, the impeller wake transported by the main flow interacts and superimposes with the gap flow and the front cascade wake, creating a new excitation source for pressure fluctuations at the rear blade leading edge. Compared with locations near the hub and tip, the pressure fluctuation at the mid-span of the front blade leading edge experiences stronger excitation from both the main flow and splitter blade wakes of the impeller.

Keywords: tandem cascade diffuser; unsteady flow; pressure fluctuation; dominant frequency

0 Introduction

High-load compressors represent the development direction of modern turbomachinery. As centrifugal compressors evolve toward higher loads, higher efficiency, and wider operating ranges, the design of their key component—the diffuser—must balance increased flow turning angles with effective control of flow losses across different operating conditions. However, the high losses of traditional single-row cascade diffusers at large incidence angles, along with severe flow separation and surge resulting from large flow turning angles, have made conventional diffusers inadequate for these development needs, necessitating the search for superior diffuser configurations.

Tandem cascade technology is considered an effective means to increase compressor loading. Wei Wei et al. analyzed the incidence angle, deviation angle, and load distribution of tandem stators, finding that the deviation angle of the front blade and the incidence angle of the rear blade are insensitive to changes in the stator inlet incidence angle, with the front blade bearing almost all load variations caused by inlet incidence changes. Hergt and Siller studied tandem design for transonic compressors and proposed three design recommendations: the front blade chord should be 30% shorter than the rear blade for optimal load balance, the axial overlap of the tandem cascade should be within 0–5% of the axial chord length, and the circumferential spacing between blades should be within 15–30% of the circumferential pitch. Payyappalli and Shine found that as the cascade pitch coefficient increases, the aerodynamic loading on the front blade becomes progressively larger compared to the rear blade. In centrifugal compressors, Douglas demonstrated that tandem centrifugal impellers can improve pressure ratio and surge margin compared to conventional single-row blades. Qi Cuixia et al. concluded that tandem cascade diffusers offer a wider operating range and higher efficiency than single-row cascade diffusers, with minimal stage losses when the pressure surface leading edge of the rear blade is positioned near the suction surface trailing edge of the front blade. Xie Rong investigated the performance of tandem cascade diffusers in centrifugal compressers, showing that airfoil quality significantly affects diffuser performance. These studies indicate that tandem cascade diffusers, compared with traditional single-row diffusers, feature larger flow turning angles, effectively prevent premature boundary layer separation, and exhibit lower flow losses, attracting increasing research interest.

Furthermore, studies have shown that internal flow in centrifugal compressors is significantly unsteady, substantially affecting aerodynamic performance in terms of efficiency, operating range, and stability. In centrifugal compressors with tandem cascade diffusers, the relatively small gap between front and rear rows creates strong and complex unsteady effects. The flow patterns, interference mechanisms, and impacts on overall machine performance and structure may differ from the unsteady flow driven by single rotor-stator interactions. While extensive research has been conducted on the geometric and aerodynamic parameters of tandem cascades, studies on their unsteady characteristics remain scarce.

This paper employs numerical simulation to investigate the unsteady flow characteristics in a tandem cascade diffuser channel under design flow conditions and explores the underlying unsteady flow mechanisms.

1 Numerical Method

For the numerical simulation of unsteady flow in the tandem cascade diffuser, the NUMECA software package was used to solve the three-dimensional unsteady Reynolds-averaged Navier-Stokes equations in cylindrical coordinates. The Spalart-Allmaras one-equation turbulence model was employed, with central difference scheme for spatial discretization. A dual-time-stepping method was used for unsteady flow field solution.

To simulate realistic inlet conditions for the tandem cascade diffuser, a centrifugal compressor stage with a tandem cascade diffuser was selected as the research object. The computational domain included the centrifugal impeller and tandem cascade diffuser. Based on the domain scaling principle, the computational domain comprised one impeller passage and two tandem cascade diffuser passages. The impeller grid contained 471,000 nodes, while the tandem cascade diffuser grid contained approximately 1.19 million nodes.

At the impeller inlet boundary, total pressure and total temperature were specified with axial inflow direction. At the tandem cascade diffuser outlet boundary, static pressure was prescribed. Periodic boundary conditions were applied in the circumferential direction. Solid walls were set as no-slip and adiabatic. In steady calculations, the rotor-stator interface used the mixing plane method, while in unsteady calculations, the sliding mesh method was employed for data transfer. The converged steady solution served as the initial field for unsteady calculations. One period was defined as the time for one impeller blade to pass through two tandem cascade diffuser passages. Each computational period consisted of 90 physical time steps, with 50 pseudo-time iterations performed at each physical time step.

2 Results and Analysis

To investigate the unsteady flow characteristics in the tandem cascade centrifugal diffuser, numerical studies were conducted under design flow conditions, analyzing the flow field and pressure fluctuations.

2.1 Unsteady Flow Field Analysis

[Figure 1: see original paper] through [Figure 3: see original paper] present instantaneous distributions of entropy increase, absolute Mach number, and absolute total pressure at 10%, 50%, and 90% span heights. At 50% span, flow separation in the front blade of the tandem cascade diffuser begins at approximately mid-chord. The separated flow area does not expand further and is blown away near the front blade trailing edge under the influence of the tandem cascade gap flow. The vortex region near the rear blade trailing edge is very small, indicating that flow separation is well controlled. Notably, the unsteady flow field, particularly in the wake region, exhibits a regular alternating high-low pattern, reflecting the transport of impeller wakes captured by the unsteady simulation. Compared with the 50% span section, the streamlines around the blades at 10% span basically follow the blade surfaces. Although the impeller wake is narrowest at this span, the wake transport phenomenon decays most slowly. At 90% span, the flow field becomes significantly more chaotic due to the combined effects of flow separation during the axial-to-radial turning near the shroud, endwall boundary layers, and the impeller outlet flow field influenced by tip clearance. Flow separation begins at the front blade leading edge, generating a counterclockwise vortex, while the separated flow near the front blade trailing edge forms a clockwise vortex under the strong influence of cascade gap flow at this spanwise location.

[Figure 4: see original paper] shows entropy increase contours at 50% span at different time instants. The entropy increase at the diffuser inlet is generally small, but increases significantly near the suction surface trailing edge of the front blade due to flow separation, indicating substantial flow losses in the front blade passage. Under the influence of the impeller wake, the entropy increase near the leading and trailing edges of both cascades varies periodically at different times. When the wake sweeps past, the entropy increase grows and the suction surface separation zone expands. Due to the influence of the tandem cascade gap flow, a significant portion of the wake flow acting on the pressure surface of the front blade is transported to the suction surface of the rear blade leading edge.

2.2 Unsteady Flow Pressure Fluctuation Analysis

[Figure 5: see original paper] illustrates the locations of pressure monitor points near the leading and trailing edges on the suction and pressure surfaces of the front and rear blades at 50% span, with corresponding monitor points also placed at 10%, 50%, and 90% span at these locations. In the following discussion, "MP5_0.5" denotes monitor point MP5 on the pressure surface at 50% span.

[Figure 6: see original paper] presents the pressure coefficient fluctuations at various monitor points over three periods. Each period shows two distinct periodic variations in the pressure coefficient near the leading edge of the front blade in the tandem cascade diffuser, corresponding to the passage of two impeller blade wakes during one period. Rotor-stator interaction occurs whenever main blades or splitter blades pass through the tandem cascade diffuser passage. Comparing pressure curves at different monitor points reveals that pressure fluctuations attenuate rapidly within the front cascade passage, while their amplitude does not change significantly within the rear cascade passage. Notably, the periodic variation pattern weakens near the leading edge of the rear blade compared with the front blade, demonstrating that the interaction between blade wake flow and gap flow in the tandem cascade gap complicates the pressure fluctuations.

[Figure 7: see original paper] shows the frequency spectrum characteristics obtained through fast Fourier transform of pressure fluctuations at different monitor points on the pressure surface at 50% span. The blade passing frequency (BPF) of the centrifugal impeller with splitter blades relative to the diffuser blades is 26.4 kHz. At 50% span, the dominant frequency of pressure fluctuation near the front blade leading edge is the impeller BPF, indicating that both main blades and splitter blades exert comparable excitation strength on the pressure fluctuation at this location. The amplitude of the dominant frequency near the front blade trailing edge is one order of magnitude smaller than that at the front blade leading edge, demonstrating substantial energy attenuation within the front cascade passage. Near the rear blade leading edge, the dominant frequency gradually shifts to 0.5 times the BPF, with amplitude slightly larger than that at the front blade trailing edge. Combined with the entropy increase distribution in [Figure 4: see original paper] and pressure fluctuation distribution in [Figure 6: see original paper], this indicates that in the gap between the two blade rows, the impeller wake transported by the main flow interacts and superimposes with the gap flow and front blade wake, impinging on the rear blade leading edge to create a new excitation source for pressure fluctuations, after which the dominant frequency of the unsteady flow becomes 0.5 times the BPF. Near the rear blade trailing edge, the dominant frequency is also 0.5 times the BPF, with amplitude slightly larger than the maximum amplitude at the rear blade leading edge, suggesting that in the main flow within the rear cascade passage, pressure fluctuation development is increasingly influenced by the tandem cascade gap and mainstream energy mixing.

[Figure 8: see original paper] presents the frequency spectrum characteristics of pressure fluctuations at different spanwise locations near the leading edge of the front blade, leading edge of the rear blade, and trailing edge of the rear blade. Near the front blade leading edge [FIGURE:8(a)], the dominant frequency at 10% and 50% span is the impeller BPF, with the sub-dominant frequency at 0.5 BPF. At 90% span, the dominant frequency becomes 0.5 BPF, with BPF as the sub-dominant frequency. The energy spectral density amplitude corresponding to BPF at 10% and 90% span is smaller than at 50% span, while the amplitude at 0.5 BPF increases with spanwise height. This indicates that compared with near-hub and near-tip regions, the pressure fluctuation at mid-span experiences stronger excitation from both main flow and splitter blade wakes, though the near-tip region shows stronger excitation from main blade wakes than mid-span and near-hub regions. Combined with [FIGURE:8(b)], this shows that within the front blade passage, pressure fluctuation energy attenuation is greater at mid-span compared with near-hub and near-tip regions. Near the rear blade leading edge [FIGURE:8(c)], the dominant frequency at 50% and 10% span develops into 0.5 BPF, with amplitude at 10% span much larger than at 50% span, while at 90% span the dominant frequency becomes the impeller BPF. Near the rear blade trailing edge [FIGURE:8(d)], the dominant frequency at 10%, 50%, and 90% span all become 0.5 BPF, with amplitude decreasing slightly with spanwise height. Combined with flow field distributions at different spans, the mixing and diffusion of high-energy fluid from mid-span toward endwalls also influences pressure fluctuations at different spans. Due to smaller flow losses in the near-hub region, pressure fluctuation energy attenuation is minimal, resulting in stronger excitation to the rear blade leading edge in the gap region.

3 Conclusions

This study investigated the unsteady flow mechanisms in a tandem cascade centrifugal diffuser, analyzing unsteady flow characteristics under design flow conditions. The main conclusions are:

1) The flow in the tandem cascade diffuser is characterized by a strongly unsteady three-dimensional viscous main flow and gap flow. Pressure fluctuation propagation attenuates rapidly within the front cascade passage, but becomes more complex within the rear cascade passage due to interactions between blade wake flow and gap flow between front and rear rows.

2) Pressure fluctuations near the leading edge of the front blades are simultaneously excited by both main blades and splitter blades of the centrifugal impeller. In the tandem cascade gap, the impeller main flow and splitter wakes transported by the mainstream mix, interact, and superimpose with the tandem cascade gap flow and the wake at the front blade trailing edge, impinging on the rear blade leading edge to create a new excitation source. The maximum amplitude and energy spectral density of the resulting pressure fluctuations are larger than those at the front blade trailing

edge. In the near-hub region, the rear blade leading edge experiences stronger pressure fluctuation excitation.

3) Within the front blade passage of the tandem cascade diffuser, the dominant frequency of pressure fluctuation is the impeller blade passing frequency. Near the rear blade leading edge, the dominant frequency shifts to 0.5 times the blade passing frequency. Near the front blade leading edge, the energy spectral density amplitude corresponding to BPF at 10% and 90% span is smaller than at 50% span. Compared with near-hub and near-tip regions, the pressure fluctuation at mid-span experiences stronger excitation from impeller main flow and splitter blade wakes. Within the front blade passage, pressure fluctuation energy attenuation is greater at mid-span than at near-hub and near-tip regions.

Note: Figure translations are in progress. See original paper for figures.

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