Flow Losses and Exit Flow Distortion in Radial Inlet Chambers: Postprint

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Abstract

The internal flow losses and outlet flow distortion of the radial inlet constitute the main factors affecting centrifugal compressor performance. To further elucidate the mechanism by which radial inlets influence centrifugal compressor performance, this study conducts a numerical investigation focusing on the aforementioned factors for an industrial centrifugal compressor radial inlet stage. The results indicate that within the normal operating range of this centrifugal compressor, the internal flow losses of the radial inlet only degrade the entire stage performance, having essentially no effect on the downstream impeller and model stage performance; whereas the flow distortion at the inlet outlet not only degrades the entire stage performance, but is also the primary cause of performance degradation in the impeller and model stage. It is hoped that this research can provide a reference basis for the improved design of radial inlets.

Full Text

Preamble

Effects of Flow Loss and Outlet Flow Distortion in Radial Inlet Chambers

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Abstract: The internal flow loss and outlet flow distortion in radial inlet chambers are the primary factors affecting centrifugal compressor performance. To further understand the underlying mechanisms of how radial inlet chambers influence centrifugal compressor performance, this paper presents a numerical investigation of these factors in an industrial centrifugal compressor stage with radial inlet.

The study reveals that within the normal operating range of the centrifugal compressor, the internal flow loss in the radial inlet chamber only degrades the overall stage performance without significantly affecting the downstream impeller or model stage performance. In contrast, the outlet flow distortion not only reduces overall stage performance but also serves as the main cause of performance degradation in the impeller and model stage. This research aims to provide reference guidance for the improved design of radial inlet chambers.

Keywords: radial inlet chamber; centrifugal compressor; flow loss; flow distortion

0 Introduction

Radial inlet chambers are critical stationary components in centrifugal compressors, serving to guide gas from intake pipelines or intercoolers to the impeller inlet [1]. Compared with axial inlet configurations, radial inlet chambers cause significant performance degradation in centrifugal compressor stages [2, 3]. Previous studies [4-7] have identified two primary mechanisms responsible for this performance reduction: First, the complex three-dimensional flow within radial inlet chambers generates local flow separation, resulting in substantial internal flow losses that reduce overall compressor performance. Second, the non-axisymmetric geometry of radial inlet chambers creates non-uniform flow parameter distributions at the chamber outlet (i.e., the impeller inlet), producing outlet flow distortion that causes the compressor stage to deviate from its design condition of axial uniform inflow, ultimately leading to decreased overall stage performance.

This paper focuses on investigating how these two factors affect both the overall stage performance and downstream components in a centrifugal compressor through numerical simulation, with the goal of further elucidating the mechanisms by which radial inlet chambers influence compressor performance and identifying the primary factors affecting performance. These findings will provide a reference basis for subsequent improvement and design optimization of radial inlet chambers.

1 Research Object

The research object is a radial inlet stage of an industrial centrifugal compressor, comprising five main components: a radial inlet chamber, impeller, vaneless diffuser, bend, and return channel. [Figure 1: see original paper] shows a schematic diagram of this compressor inlet stage, while [Figure 2: see original paper] presents a three-dimensional perspective model of the radial inlet chamber. Due to the circumferential non-uniformity of the flow at the inlet chamber outlet, full-channel grids were employed for the impeller, diffuser, bend, and return channel. The complete stage grid model is shown in [Figure 3: see original paper], with grid refinement applied at all solid walls to account for boundary layer effects.

2.1 Computational Code

This study utilizes the commercial software FINE/Turbo from NUMECA to solve the three-dimensional compressible Reynolds-averaged Navier-Stokes (RANS) equations. The Jameson central difference scheme combined with the Spalart-Allmaras one-equation low-Reynolds-number turbulence model was employed for the solution. Artificial viscosity coefficients were added to ensure convergence, and a full multi-grid method combined with variable time stepping and residual smoothing was used to accelerate convergence.

2.2 Computational Grid

The centrifugal compressor model with radial inlet chamber was divided into three grid domains: the radial inlet chamber, the impeller and diffuser, and the bend and return channel. To capture the circumferential flow non-uniformity at the inlet chamber outlet, full-channel grids were used for the impeller, diffuser, bend, and return channel. The complete stage grid model is shown in [Figure 3: see original paper], with grid refinement applied at all solid walls to account for boundary layer effects. Information transfer between rotating and stationary components was handled using the Frozen Rotor Approach [8].

2.3 Boundary Conditions

For the numerical simulations, total temperature and total pressure were specified at the compressor inlet boundary (the "in" section shown in [Figure 1: see original paper]), with the flow direction normal to the inlet plane. At the outlet boundary (the "out" section), mass flow rate was specified. All rotating walls were assigned the operating rotational speed, while other walls were set to stationary. All walls were treated as adiabatic smooth surfaces with no-slip boundary conditions.

3 Research Methodology

To investigate the effects of internal flow loss and outlet flow distortion in the radial inlet chamber on centrifugal compressor performance, two comparative models were established for comparison with the original radial inlet model. All models share the same inlet and outlet sections and corresponding boundary conditions; they differ only in the assumed internal flow conditions within the radial inlet chamber (see):

- **Model A:** Assumes no flow loss within the radial inlet chamber and no flow distortion at the chamber outlet. Therefore, the flow at Section 0 is uniformly distributed and enters the impeller axially, with total temperature and total pressure identical to those at the "in" section of the original model.

- **Model B:** Assumes flow loss exists within the radial inlet chamber but no flow distortion at the chamber outlet. Therefore, the flow at Section 0 remains uniformly distributed and enters the impeller axially, with total temperature and total pressure identical to those at Section 0 of the original radial inlet model.

Since the internal flow conditions in the radial inlet chamber are hypothetical in these models, the actual computational domain extends from Section 0 to the "out" section, encompassing the impeller, vaneless diffuser, bend, and return channel. Given that both Models A and B have no flow distortion at the inlet chamber outlet (Section 0), satisfying the condition of axial uniform inflow at the impeller inlet, single-passage grid models were used for these calculations, with the mixing-plane method [8] employed at rotor-stator interfaces.

4 Results and Analysis

To examine the effects of internal flow loss and outlet flow distortion in the radial inlet chamber on both overall stage performance and downstream components, this paper compares the overall stage efficiency (_in-out), model stage efficiency (_0-out), and impeller efficiency (_0-2) across different models. The efficiency definitions for each component are provided in , where the model stage efficiency _0-out reflects the overall performance of all downstream components affected by the radial inlet chamber.

The comparison between the original model and Model A reflects the overall impact of the radial inlet chamber on compressor performance, including the combined effects of internal flow loss and outlet flow distortion. The comparison between the original model and Model B isolates the effect of outlet flow distortion, while the comparison between Models A and B reveals the effect of internal flow loss.

4.1 Effects on High-Efficiency Point Performance

[Figure 4: see original paper] compares the component efficiencies of different models at the high-efficiency operating point. Compared with Model A, the original model (which includes both internal flow loss and outlet flow distortion) shows a 2.6% decrease in overall stage efficiency, a 1.4% decrease in model stage efficiency, and a 1.3% decrease in impeller efficiency.

Compared with Model B, the outlet flow distortion in the original model causes a 1.6% decrease in overall stage efficiency, a 1.4% decrease in model stage efficiency, and a 1.2% decrease in impeller efficiency. In contrast, the comparison between Models A and B indicates that internal flow loss alone only reduces overall stage efficiency by 1%, with essentially no impact on model stage or impeller performance.

4.2 Effects on Performance Curves

[Figure 5: see original paper] through [Figure 7: see original paper] compare the performance curves of different models for the overall stage and individual components. The horizontal axis _ref represents the relative flow coefficient, defined as the ratio of the flow coefficient at a given operating point to that at the high-efficiency point.

Comparing the performance curves of the original model and Model A in [Figure 5: see original paper] reveals that the combined effects of internal flow loss and outlet flow distortion from the radial inlet chamber produce essentially uniform effects on overall stage performance across the entire normal operating range, reducing performance by an average of 3%. The comparison between Models A and B shows that the effect of internal flow loss on overall stage performance increases with flow rate. [Figure 5: see original paper] also demonstrates that when _ref < 1.15, the effect of outlet flow distortion on overall stage performance exceeds that of internal flow loss; only when _ref > 1.2 does the internal flow loss effect become slightly greater than the distortion effect.

As clearly shown in [Figure 6: see original paper] and [Figure 7: see original paper], throughout the compressor' s entire normal operating range, the performance curves for the model stage and impeller in Models A and B essentially overlap. This indicates that internal flow loss in the radial inlet chamber has virtually no effect on model stage and impeller performance across the operating range, while outlet flow distortion is the primary cause of performance degradation in these components.

4.3 Analysis and Discussion

The computational results demonstrate that both internal flow loss and outlet flow distortion in radial inlet chambers are indeed the main factors affecting centrifugal compressor stage performance. For the compressor studied here, outlet flow distortion has a greater adverse effect on stage performance across most operating conditions. At the high-efficiency point, internal flow loss has essentially no effect on model stage performance, impacting only the overall stage efficiency, whereas outlet flow distortion significantly affects model stage performance, causing noticeable efficiency reductions in the impeller and other downstream components.

Comparisons of performance curves across different models further reveal that throughout the entire normal operating range, internal flow loss in the radial inlet chamber affects only overall stage performance without impacting downstream components (impeller and model stage), and this effect increases with flow rate. In contrast, outlet flow distortion at the chamber cross-section significantly impacts downstream component performance and represents the primary cause of efficiency degradation in the impeller and model stage.

This occurs mainly because outlet flow distortion alters the ideal condition of axial uniform inflow at the impeller inlet, deteriorating the internal flow conditions within the impeller and downstream components and reducing the impeller' s work capacity. Furthermore, across most of the compressor' s operating conditions, outlet flow distortion from the radial inlet chamber has a greater impact on overall stage performance.

These findings suggest that in radial inlet chamber improvement studies, reducing internal flow loss alone can only enhance overall stage performance without affecting downstream components (particularly the impeller), thereby providing limited performance improvement. In contrast, reducing outlet flow distortion can effectively improve impeller and model stage performance, fundamentally enhancing overall stage performance. Additionally, outlet flow distortion subjects the impeller to periodic loading, affecting its service life [9, 10]. Therefore, greater emphasis should be placed on minimizing outlet flow distortion in the design and improvement of radial inlet chambers.

5 Conclusions

This study investigates the effects of internal flow loss and outlet flow distortion in radial inlet chambers on both overall stage performance and downstream components of centrifugal compressors through numerical methods. The main conclusions are:

1. Both internal flow loss and outlet flow distortion in radial inlet chambers are indeed the primary mechanisms through which these components affect centrifugal compressor stage performance. For the compressor studied, outlet flow distortion has a greater detrimental effect on stage performance across most operating conditions.
2. Throughout the entire normal operating range of the centrifugal compressor, internal flow loss in the radial inlet chamber only degrades overall stage performance without significantly affecting downstream impeller and model stage performance. In contrast, outlet flow distortion not only reduces overall stage performance but also serves as the main cause of impeller and model stage performance degradation.

It is hoped that this research can further elucidate the mechanisms by which radial inlet chambers influence centrifugal compressor performance and provide reference guidance for future improvement and design optimization of radial inlet chambers.

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