Postprint on the Effects of Flow Losses and Exit Flow Distortion in Radial Inlet

Authors: Han Fenghui1, Mao Yijun 1, Tan Jiajian 2

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Abstract

The internal flow losses and outlet flow distortion of radial inlet chambers constitute the primary factors influencing centrifugal compressor performance. To further elucidate the underlying mechanism by which radial inlet chambers affect centrifugal compressor performance, this study conducts a numerical investigation on the radial inlet stage of an industrial centrifugal compressor, focusing on the aforementioned factors. The results demonstrate that within the normal operating range of this centrifugal compressor, the internal flow losses of the radial inlet chamber only degrade the overall stage performance, essentially exerting no influence on the performance of the downstream impeller and model stage; conversely, the flow distortion at the inlet chamber outlet not only deteriorates the overall stage performance, but also serves as the main cause of performance degradation in both the impeller and model stage. It is hoped that this research can provide a reference basis for the improved design of radial inlet chambers.

Full Text

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

Han Fenghui[1], Mao Yijun[1], Tan Jiajian[2]
[1]School of Energy and Power Engineering, Xi' an Jiaotong University, Xi' an 710049, China
[2]Department of Research & Development, Shenyang Blower Works Group Co., Ltd., Shenyang 110869, China

Abstract: Flow loss and outlet flow distortion in radial inlet chambers are the primary mechanisms through which these components affect centrifugal compressor performance. To further understand the underlying physics, this paper presents a numerical investigation of an industrial centrifugal compressor stage with radial inlet, focusing on these two factors. The results demonstrate that within the compressor's normal operating range, internal flow losses in the radial inlet chamber only degrade the overall stage performance without significantly affecting the downstream impeller or model stage. In contrast, outlet flow distortion from the inlet chamber not only reduces overall stage performance but also represents the main cause of performance degradation in the impeller and model stage. This research provides valuable references for the improved design of radial inlet chambers.

Keywords: radial inlet; centrifugal compressor; flow loss; flow distortion
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0 Introduction

The radial inlet chamber is a critical stationary component in centrifugal compressors, serving to guide gas from the intake pipeline or intercooler 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 drop: 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 model stage to deviate from its design condition of axial uniform inflow, ultimately leading to decreased stage performance. This numerical study investigates how these two factors affect both the entire centrifugal compressor stage and its downstream components, aiming to deepen understanding of the physical mechanisms through which radial inlet chambers influence compressor performance and identify the dominant factors affecting performance, thereby providing reference guidance for subsequent design improvements.

1 Research Object

The research object is the 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 the compressor stage, while [Figure 2: see original paper] presents a three-dimensional perspective view of the radial inlet chamber.

2 Numerical Methodology

2.1 Solver

This study employs the commercial CFD code 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 is used for the solution. Artificial viscosity coefficients are added to ensure convergence, and convergence acceleration is achieved through a full multigrid method with variable time stepping and residual smoothing.

2.2 Computational Grid

The computational domain for the centrifugal compressor with radial inlet is divided into three parts: the radial inlet chamber, the impeller and diffuser, and the bend and return channel. Given the circumferential non-uniformity of the flow at the inlet chamber outlet, full passage grids are adopted for the impeller, diffuser, bend, and return channel. The grid distribution is illustrated in [Figure 3: see original paper]. To account for boundary layer effects, grid refinement is applied at all solid walls. Information transfer across rotor-stator interfaces is handled using the Frozen Rotor Approach [8].

2.3 Boundary Conditions

For the numerical simulations, total temperature and total pressure are specified at the compressor inlet boundary (the "in" plane shown in [Figure 1: see original paper]), with the flow direction normal to the inlet plane. At the outlet boundary (the "out" plane), mass flow rate is prescribed. All rotating walls are assigned the corresponding rotational speed, while stationary walls have zero rotational speed. All walls are 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 identical inlet and outlet boundaries with corresponding boundary conditions; they differ only in the assumed flow conditions within the radial inlet chamber (see):

- **Model A** assumes no flow loss in the radial inlet chamber and no flow distortion at the chamber outlet. Consequently, the flow at Plane 0 is uniform and enters the impeller axially, with total temperature and total pressure identical to those at the "in" plane in the original model.
- **Model B** assumes flow loss exists in the radial inlet chamber but no flow distortion at the chamber outlet. Thus, the flow at Plane 0 remains uniform and axial, but with total temperature and total pressure matching those at Plane 0 in 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 Plane 0 to the "out" plane, 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 (Plane 0), satisfying the condition of axial uniform inflow, single-passage grids are used for these models with the mixing plane method [8] applied at rotor-stator interfaces.

TABLE:1 Assumptions for internal flow conditions in radial inlet chamber

4 Results and Analysis

To examine the influence of radial inlet chamber internal flow loss and outlet distortion on both the entire stage and downstream components, this paper compares the overall stage efficiency η_{in-out}, model stage efficiency η_{0-out}, and impeller efficiency η_{02} across different models. The efficiency definitions are provided in **TABLE:2**, where the model stage efficiency η_{0-out} reflects the overall performance impact on all downstream components.

TABLE:2 Definitions of performance parameters

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

4.1 Performance at High-Efficiency Operating Point

[Figure 4: see original paper] compares component efficiencies across different models at the high-efficiency operating point. Compared with Model A, the original model incorporating both internal flow loss and outlet 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.

Relative to Model B, the outlet flow distortion in the original model reduces overall stage efficiency by 1.6%, model stage efficiency by 1.4%, and impeller efficiency by 1.2%. The comparison between Models A and B indicates that internal flow loss alone only decreases overall stage efficiency by 1%, with virtually no impact on model stage and impeller performance.

4.2 Effects on Performance Characteristics

Figures 5 through 7 [Figure 7: see original paper] present performance curve comparisons for the different models. The horizontal axis represents the relative flow coefficient ϕ/ϕ_{ref}, defined as the ratio of the flow coefficient at a given operating point to that at the high-efficiency point ϕ_{ref}.

Comparing the performance curves of the original model and Model A in [Figure 5: see original paper] reveals that the combined effect of internal flow loss and outlet distortion reduces overall stage performance by approximately 3% across the entire normal operating range. 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 indicates that when ϕ/ϕ_{ref} is less than 1.15, the effect of outlet flow distortion on overall stage performance exceeds that of internal flow loss. Only when ϕ/ϕ_{ref} exceeds 1.2 does the internal flow loss effect become slightly greater than the outlet distortion effect.

As clearly shown in Figures 6 and 7, the performance curves for the model stage and impeller in Models A and B essentially coincide across the entire normal operating range. This demonstrates that internal flow loss in the radial inlet chamber has negligible effect on model stage and impeller performance, while outlet flow distortion is the primary cause of performance degradation in these components.

4.3 Discussion

The computational results confirm 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 investigated in this study, outlet flow distortion has a greater adverse effect on stage performance across most operating conditions. At the high-efficiency point, internal flow loss has virtually no impact on model stage performance, affecting only the overall stage efficiency, whereas outlet flow distortion significantly degrades model stage performance, causing noticeable efficiency reductions in the impeller and other downstream components.

Performance curve comparisons further demonstrate that throughout the entire normal operating range, internal flow loss in the radial inlet chamber only affects overall stage performance without impacting downstream components, and this effect grows with increasing flow rate. In contrast, outlet flow distortion significantly affects downstream component performance and represents the primary cause of efficiency degradation in the impeller and model stage.

This occurs primarily 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. Moreover, across most of the compressor' s operating range, 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 can only enhance overall stage performance without benefiting downstream components (particularly the impeller), thereby providing limited performance improvement. However, 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, potentially affecting its service life [9, 10].

Therefore, the influence of outlet flow distortion should receive greater attention in the design and improvement of radial inlet chambers.

5 Conclusions

This study employs numerical methods to investigate the effects of internal flow loss and outlet flow distortion in radial inlet chambers on both overall stage and downstream component performance of a centrifugal compressor. The main conclusions are:

1) Internal flow loss and outlet flow distortion in radial inlet chambers are indeed the primary mechanisms affecting centrifugal compressor stage performance. For the compressor studied herein, outlet flow distortion has a more 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 the downstream impeller and model stage. In contrast, outlet flow distortion not only reduces overall stage performance but also represents the main cause of performance degradation in the impeller and model stage.

It is hoped that this research provides deeper insight into the physical mechanisms through which radial inlet chambers affect centrifugal compressor performance, thereby offering valuable references for future design improvements.

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